GEORGIA INSTITUTE OF TECHNOLOGY **OFFICE OF CONTRACT ADMINISTRATION**

PROJECT ADMINISTRATION DATA SHEET

[XX] ORIGINAL [ ] REVISION NO. ______

Project No. E-20-G09 (R6183-0A0) GTRC/~~GIT~~ DATE 8 / 22/86

Project Director: B.J. Goodno School/~~Lab~~ CE

Sponsor: National Science Foundation

Type Agreement: Grant No. ECE-8610929

Award Period: From 6/1/86 To ~~5/31/88*~~ 11/30/88 (Performance) 8/31/88 (Reports)

Sponsor Amount:

	This Change	Total to Date
Estimated:	$	$ 92,091
Funded:	$	$ 92,091

Cost Sharing Amount: $ ______ Cost Sharing No: E-20-327

Title: Behavior of Architectural Nonstructural Components in the Mexico Earthquake.

ADMINISTRATIVE DATA

OCA Contact John B. Schonk ext. 4820

1) Sponsor Technical Contact:

A. Eggenberg
National Science Foundation
ENG/ECE
Washington, DC 20550

202/357-9500

2) Sponsor Admin/Contractual Matters:

C.T. Henney
National Science Foundation
DGC/ENG
Washington, DC 20550

202/357-9626

Defense Priority Rating: N/A

Military Security Classification: N/A
(or) Company/Industrial Proprietary: N/A

RESTRICTIONS

See Attached NSF Supplemental Information Sheet for Additional Requirements.

Travel: Foreign travel must have prior approval – Contact OCA in each case. Domestic travel requires sponsor approval where total will exceed greater of $500 or 125% of approved proposal budget category.

Equipment: Title vests with GIT

COMMENTS:

* Includes a 6 month unfunded flexibility period
No funds may be expended after 5/31/88
Distribution of awarded funds is as follows: E-20-G09 = $92,091
E-16-645 = 39,407
Total $131,498

AUG 1986 RECEIVED SUPPORT SER OCA

COPIES TO:

SPONSOR'S I. D. NO. 02.107.000.86.R88

Project Director
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GEORGIA INSTITUTE OF TECHNOLOGY
OFFICE OF CONTRACT ADMINISTRATION

NOTICE OF PROJECT CLOSEOUT

Date 5/22/89

Project No. E-20-G09 Center No. R6183-0A0

Project Director B. J. Goodno School/Lab CE

Sponsor National Science Foundation

Contract/Grant No. ECE-8610929 GTRC XX GIT ___

Prime Contract No. ___

Title Behavior of Architectural Nonstructural Components in the Mexico Earthquake

Effective Completion Date 11/30/88 (Performance) 2/28/89 (Reports)

Closeout Actions Required:

- X None
- ___ Final Invoice or Copy of Last Invoice
- ___ Final Report of Inventions and/or Subcontracts
- ___ Government Property Inventory & Related Certificate
- ___ Classified Material Certificate
- ___ Release and Assignment
- ___ Other ___

Includes Subproject No(s). E-16-645/Craig/AE

Subproject Under Main Project No. ___

Continues Project No. ___ Continued by Project No. ___

Distribution:

- x Project Director
- x Administrative Network
- x Accounting
- x Procurement/GTRI Supply Services
- x Research Property Management
- ___ Research Security Services
- x Reports Coordinator (OCA)
- x GTRC
- x Project File
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- x Other E-16-645/Craig/AE

NATIONAL SCIENCE FOUNDATION
Washington, D.C. 20550

FINAL PROJECT REPORT
NSF FORM 98A

PLEASE READ INSTRUCTIONS ON REVERSE BEFORE COMPLETING

PART I—PROJECT IDENTIFICATION INFORMATION

1. Institution and Address	2. NSF Program	3. NSF Award Number
School of Civil Engineering Georgia Institute of Technology Atlanta, Georgia 30332-0355	Earthquake Hazards Mitigation	ECE-8610929
	4. Award Period From June '86 To Nov.1988	5. Cumulative Award Amount $131,498

6. Project Title

BEHAVIOR OF ARCHITECTURAL NONSTRUCTURAL COMPONENTS IN THE MEXICO EARTHQUAKE

PART II—SUMMARY OF COMPLETED PROJECT *(FOR PUBLIC USE)*

The research program consisted of a combined field study of building cladding performance during the 1985 Mexico earthquake and supporting analytical and experimental studies of cladding connection systems typical of practice in Mexico City. This research effort was broken down into three phases:

1. Phase I: Nonstructural damage survey and evaluation for selected buildings in Mexico City.

Perishable data on damage to building architectural components and contents was obtained but valuable data was lost as buildings were demolished or cosmetic repairs were made to return buildings to service as rapidly as possible. Nonetheless, from the survey of 25 buildings with heavy cladding systems in Mexico City, 10 of 18 buildings on the lake bed showed good cladding performance, 3 of 18 showed fair performance, and 5 of 18 were rated as having poor cladding performance; all 7 of the buildings on the transition zone had good cladding performance.

2. Phase II: Laboratory testing of cladding connections representative of Mexican practice.

Laboratory testing of typical cladding connection designs was carried out to determine their behavior and to calibrate analytical models developed under Phase III. Panel inserts were tested to failure in pullout, shear, and moment. Hysteretic behavior, damping and ductility values were determined from the test results.

3. Phase III: Analytical evaluation of case study buildings for cladding-structure interaction effects.

One of the Phase I buildings was studied in detail to explain observed damage to both the structure and cladding. Three-dimensional finite element models of both cladding and structure were assembled. The computer models predicted that cladding connection failure would occur at the attachment points at force levels substantially less than those calculated for the building using available ground motion records.

The principal findings of this research investigation are: (1) More than 25% of the Phase I buildings suffered serious damage to the heavy precast cladding; (2) Improper design of building cladding can have a detrimental effect on the overall performance of structures during earthquakes; (3) Some of the observed field repairs to damaged cladding connections may have been carried out improperly due to lack of understanding of the forces and movements experienced by cladding in an actual earthquake; this could lead to serious problems in the future.

The authors are confident that rational engineering principles can be applied to the design of cladding systems on buildings. It is also possible that heavy cladding systems will be used in the future for both lateral stiffening and increased damping in buildings.

PART III—TECHNICAL INFORMATION *(FOR PROGRAM MANAGEMENT USES)*

1. ITEM *(Check appropriate blocks)*	NONE	ATTACHED	PREVIOUSLY FURNISHED	TO BE FURNISHED SEPARATELY TO PROGRAM: Check (✓)	Approx. Date
a. Abstracts of Theses		X			
b. Publication Citations		X			
c. Data on Scientific Collaborators		X			
d. Information on Inventions	X				
e. Technical Description of Project and Results		X			
f. Other *(specify)*					

2. Principal Investigator/Project Director Name *(Typed)*	3. Principal Investigator/Project Director Signature	4. Date
Barry J. Goodno		May 12, 1989

PART IV - SUMMARY DATA ON PROJECT PERSONNEL

NSF Division Earthquake Hazards Mitigation

The data requested below will be used to develop a statistical profile on the personnel supported through NSF grants. The information on this part is solicited under the authority of the National Science Foundation Act of 1950, as amended. All information provided will be treated as confidential and will be safeguarded in accordance with the provisions of the Privacy Act of 1974. NSF requires that a single copy of this part be submitted with each Final Project Report (NSF Form 98A); however, submission of the requested information is not mandatory and is not a precondition of future awards. If you do not wish to submit this information, please check this box ☐

Please enter the numbers of individuals supported under this NSF grant.
Do not enter information for individuals working less than 40 hours in any calendar year.

*U.S. Citizens/ Permanent Visa	PI's/PD's		Post-doctorals		Graduate Students		Under-graduates		Precollege Teachers		Others	
	Male	Fem.	Male	Fem.	Male	Fem.	Male	Fem.	Male	Fem.	Male	Fem.
American Indian or Alaskan Native												
Asian or Pacific Islander												
Black, Not of Hispanic Origin					1							
Hispanic												
White, Not of Hispanic Origin	2				2							
Total U.S. Citizens	2				3							
Non U.S. Citizens			1		4							
Total U.S. & Non-U.S. ..	4		1		7							
Number of individuals who have a handicap that limits a major life activity.	none											

*Use the category that best describes person's ethnic/racial status. (If more than one category applies, use the one category that most closely reflects the person's recognition in the community.)

AMERICAN INDIAN OR ALASKAN NATIVE: A person having origins in any of the original peoples of North America, and who maintains cultural identification through tribal affiliation or community recognition.

ASIAN OR PACIFIC ISLANDER: A person having origins in any of the original peoples of the Far East, Southeast Asia, the Indian subcontinent, or the Pacific Islands. This area includes, for example, China, India, Japan, Korea, the Philippine Islands and Samoa.

BLACK, NOT OF HISPANIC ORIGIN: A person having origins in any of the black racial groups of Africa.

HISPANIC: A person of Mexican, Puerto Rican, Cuban, Central or South American or other Spanish culture or origin, regardless of race.

WHITE, NOT OF HISPANIC ORIGIN: A person having origins in any of the original peoples of Europe, North Africa or the Middle East.

THIS PART WILL BE PHYSICALLY SEPARATED FROM THE FINAL PROJECT REPORT AND USED AS A COMPUTER SOURCE DOCUMENT. DO NOT DUPLICATE IT ON THE REVERSE OF ANY OTHER PART OF THE FINAL REPORT.

FINAL PROJECT REPORT

NSF Award No. ECE-8610929
BEHAVIOR OF ARCHITECTURAL NONSTRUCTURAL COMPONENTS IN THE MEXICO EARTHQUAKE
June 1986 - November 1988

Professors Barry J. Goodno and James I. Craig
Co-Principal Investigators
Georgia Institute of Technology
Atlanta, Georgia 30332-0355

PART III - TECHNICAL INFORMATION

a. Abstracts of Theses

The following student research activities have been, or are currently being, carried out on the subject grant. A report abstract is attached for report 1.

1) Ralf Leistikow (MSCE, March 1988)

   "The Behavior of the Ductile Rod/Push-Pull Connection for Precast Cladding Panels"

2) George P. Wheatley (MSCE, in progress - expected completion 1/90)

   Study of design and construction of prefabricated brick masonry cladding systems

3) Satish Nagarajaiah (MSCE, in progress - expected completion 9/89)

   Development of a three dimensional superelement model of precast cladding systems

4) Clarence J. Fennell, (Ph.D., in progress - expected completion 12/89)

   "Experimental Evaluation of Connections for Heavy Cladding Systems"

5) Mr. Loai El-Gazairly (Ph.D., in progress - expected completion 9/90)

   "Analytical Studies of Building and Cladding Damage in a Major Earthquake"

6) Mr. Jean-Paul Pinelli (Ph.D., in progress - expected completion 1/91)

   "Analytical and Experimental Evaluation of Panel Inserts in Shear, Bending and Pull-out"

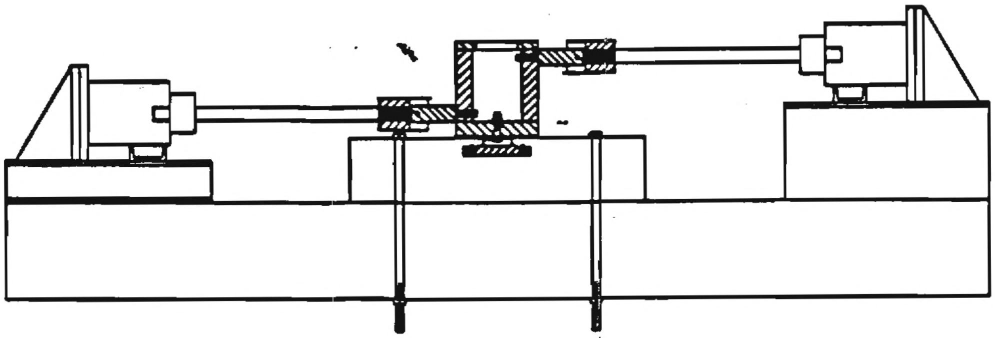

Figure 1. Typical Test Configuration for Combined Shear and Bending Tests of Cladding Connection.

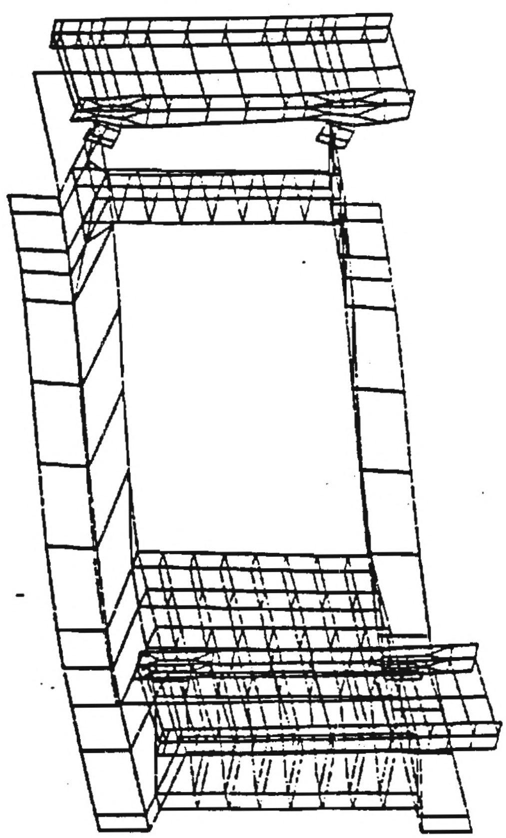

Figure 2. Deformed View of Complete Cladding Panel, Connection, Spandrel Beam Model.

7) Mr. Bilal El-Ariss (Ph.D., in progress - expected completion 6/91)

"Advanced Connections for Cladding With Improved Ductility and Damping Characteristics"

b. Publication Citations

1. Goodno, B.J., and Pinelli, J.P., "The Role of Cladding in Seismic Response of Lowrise Buildings in the Southeastern U.S.," Proceedings, The Third U.S. National Conference on Earthquake Engineering, held in Charleston, S.C., on August 24-28, 1986, Vol. II, pp. 883-894.

2. Goodno, B.J., and Naman, S.K., "Earthquake Analysis of Lowrise Buildings in Zones of Moderate Seismicity," Proceedings, Eighth European Conference on Earthquake Engineering, held in Lisbon, Portugal, on September 7-12, 1986, Vol. 8, pp. 79-86.

3. Goodno, B.J., "Cladding-Structure Interaction: The State of the Art," Invited Presentation, 1986 ASCE Structures Congress, held in New Orleans, La., Sept. 15-18, 1986 (see Structures Congress '86 Abstracts, ASCE, p. 271).

4. Goodno, B.J., "Static and Dynamic Analysis of Highrise Buildings on Microcomputers," Proceedings, Fourth Conference on Computing in Civil Engineering, ASCE, held in Boston, MA, October 27-31, 1986, pp. 300-315.

5. Goodno, B. J., and Streit, M. C., "Seismic Response Analysis of Low Rise Buildings Using Microcomputers," Proceedings, The 4th National Conference on Microcomputers in Civil Engineering, held in Orlando, Florida, on November 5-7, 1986, pp. 262-266.

6. Goodno, B. J., Craig, J. I., and Zeevaert-Wolff, "Behavior of Architectural Nonstructural Components in the Mexico Earthquake - First Progress Report," Proceedings, First U.S.-Mexico Workshop on 1985 Mexico Earthquake Research, held in Mexico City on November 16-18, 1986, pp. 85-90, published by Earthquake Engineering Research Institute (EERI), April 1987.

7. Goodno, B. J., Craig, J. I., and Zeevaert-Wolff, "Behavior of Architectural Nonstructural Components in the Mexico Earthquake - Second Progress Report," Proceedings, 2ND U.S.-Mexico Workshop on 1985 Mexico Earthquake Research, held in Mexico City on November 5-7, 1987, 6 pages, published by Earthquake Engineering Research Institute (EERI), November 1987.

8. Goodno, B. J., "Cladding-Structure Interaction: Overview of Past Research," National Center for Earthquake Engineering Research, SUNY, Buffalo, NY, February 18, 1988.

9. Goodno, B. J., "Effect of Non-Structural Elements on Earthquake Response of Buildings - Theoretical Aspects," presented at the Conference on Tall Buildings in Seismic Regions sponsored by the Council on Tall Buildings and Urban Habitat, in Los Angeles, California, on February 25-26, 1988.

10. Craig, J. I., "Effect of Non-Structural Elements on Earthquake Response of Buildings - Experimental Aspects," presented at the Conference on Tall Buildings in Seismic Regions sponsored by the Council on Tall Buildings and Urban Habitat, in Los Angeles, California, on February 25-26, 1988.

11. Craig, J. I., and Goodno, B. J., "Cladding-Structure Interaction: Modeling and Performance of Connections," presented by J. I. Craig at the ACI Annual Convention, Session on Design, Fabrication and Erection of Precast Wall Panels, Committee 533 (Precast Panels), in Orlando, Florida, on March 25, 1988.

12. Meyyappa, M., Goodno, B. J., and Fennell, C. J., "Modeling and Performance of Precast Cladding Connections," Proceedings, The Fifth ASCE Specialty Conference on Computing in Civil Engineering, held in Alexandria, Va., on March 29-31, 1988, pp. 209-218.

13. Goodno, B. J., Craig, J. I., and Zeevaert-Wolff, "Behavior of Architectural Nonstructural Components in the Mexico Earthquake - Third Progress Report," 7 pages, Earthquake Engineering Research Institute (EERI), May 1988.

14. Goodno, B. J., Meyyappa, M., and Nagarajaiah, S., "A Refined Model for Precast Cladding and Connections," to appear in the Proceedings of the 9th World Conference on Earthquake Engineering, held in Tokyo and Kyoto, Japan on August 2-9, 1988, 6 pages.

15. Palsson, H., and Goodno, B. J., "Influence of Interstory Drift on Cladding Panels and Connections," to appear in the Proceedings of the 9th World Conference on Earthquake Engineering, held in Tokyo and Kyoto, Japan on August 2-9, 1988, 6 pages.

16. Craig, J. I., Fennell, C. J., and Leistikow, R., "Experimental Studies of the Performance of Precast Cladding Connections," to appear in the Proceedings of the 9th World Conference on Earthquake Engineering, held in Tokyo and Kyoto, Japan on August 2-9, 1988, 6 pages.

17. Goodno, B. J., and Craig, J. I., "Advanced Seismic Design Methods for Precast Cladding," presented by B. Goodno at The Precast Seismic Structural Systems Workshop, held in La Jolla, California, on November 20-21, 1988 (see Precast Seismic Structural Systems Workshop: Research Briefs, Report No. SSRP-88/08, Dept. of Applied Mechanics and Engineering Sciences, University of California, San Diego, ed. by M. J. Nigel Priestley).

18. Goodno, B. J., Craig, J. I., and Zeevaert-Wolff, "Behavior of Architectural Nonstructural Components in the Mexico Earthquake - Final Progress Report," 10 pages, Earthquake Engineering Research Institute (EERI), January 1989.

19. Goodno, B. J., Craig, J. I., and Zeevaert Wolff, A., "Behavior of Heavy Cladding Components in the Mexico Earthquake," Earthquake Spectra, EERI, Vol. 5, No. 1, February 1989, pp. 195-222.

20. El-Gazairly, Loai F., and Goodno, B. J., "Dynamic Analysis of a Highrise Building Damaged in the Mexico Earthquake Including Cladding-Structure Interaction," abstract submitted in February 1989 for review for possible presentation at the International Symposium on Architectural Precast Cladding - Its Contribution to Lateral Resistance of Buildings, organized by the Prestressed Concrete Institute, to be held in Chicago, Illinois, November 8-9, 1989.

21. Pinelli, Jean-Paul, and Craig, J. I., "Experimental Studies of the Performance of Mexican Precast Cladding Connections," abstract submitted in February 1989 for review for possible presentation at the International Symposium on Architectural Precast Cladding - Its Contribution to Lateral Resistance of Buildings, organized by the Prestressed Concrete Institute, to be held in Chicago, Illinois, November 8-9, 1989.

22. Pinelli, Jean-Paul, El-Ariss, Bilal, Craig, J. I., and Goodno, B. J., "Development and Experimental Calibration of Selected Dynamic Models for Precast Cladding Connections," abstract submitted in May 1989 for review for possible presentation at the Fourth U.S. National Conference on Earthquake Engineering, to be held in Palm Springs, California, on May 20-24, 1990.

23. El-Gazairly, Loai F., Goodno, B. J., and Craig, J. I., "Analytical Investigation of Advanced Connections for Precast Cladding on Buildings," abstract submitted in May 1989 for review for possible presentation at the Fourth U.S. National Conference on Earthquake Engineering, to be held in Palm Springs, California, on May 20-24, 1990.

c. Data on Scientific Collaborators

1. Dr. Barry J. Goodno, Professor, School of Civil Engineering, Georgia Institute of Technology, Co-Principal Investigator, Project Director

2. Dr. James I. Craig, Professor, School of Aerospace Engineering, Georgia Institute of Technology, Co-Principal Investigator

3. Dr. Murugappan Meyyappa, Research Engineer, School of Aerospace Engineering

4. Mr. Clarence J. Fennell, Graduate Research Assistant, School of Civil Engineering (Ph.D. candidate)

5. Mr. Ralf Leistikow, Graduate Research Assistant, School of Civil Engineering (MSCE, March 1988)

6. Mr. Satish Nagarajaiah, Graduate Research Assistant, School of Civil Engineering (currently at SUNY, Buffalo, NY)

7. Mr. George P. Wheatley, Graduate Research Assistant, School of Civil Engineering

8. Mr. Loai El-Gazairly, Graduate Research Assistant, School of Civil Engineering

9. Mr. Jean-Paul Pinelli, Graduate Research Assistant, School of Civil Engineering

10. Mr. Bilal El-Ariss, Graduate Research Assistant, School of Civil Engineering

d. <u>Information on Inventions</u>

None

e. <u>Technical Description of Project and Results</u>

A technical description of the research project and results to date is presented in the above publications (see Section b. above) and in a proposal for follow-on and related research:

> **Advanced Seismic Design Methods for Precast Cladding**, National Science Foundation, Earthquake Hazards Mitigation, submitted December 1988 (currently under review). (A preliminary version of this proposal was presented at the PRESSS Workshop, U.C. San Diego, November 1988 - see publication citation b.17 above)

Copies of publications 6, 7, 13, 18 and 19 (see Sec. b above), which directly relate to research progress on this grant, are attached.

f. <u>Other</u>

None

REPORT ABSTRACT FOR REPORT (1) IN SECTION (a), PART III

A report title page and abstract are attached for the following report:

1) Ralf Leistikow (MSCE, March 1988)

"The Behavior of the Ductile Rod/Push-Pull Connection for Precast Cladding Panels"

THE BEHAVIOR OF THE DUCTILE ROD/PUSH-PULL CONNECTION FOR PRECAST CLADDING PANELS

A SPECIAL RESEARCH PROBLEM

Presented to

The Faculty of the School of Civil Engineering

by

Ralf Leistikow

In Partial Fulfillment of the

Requirements for the Degree of

Master of Science in Civil Engineering

Georgia Institute of Technology

March 1988

Approved:

Dr. Barry J. Goodno/Date
Faculty Advisor

Dr. James I. Craig
Member of Reading Committee

ABSTRACT

This report presents the results of a study of the mechanical performance of push-pull (ductile rod) connections typically employed on the West Coast of the United States for earthquake isolation of architectural precast cladding panels. The tests were carried out on specially designed laboratory specimens using a fixture that was capable of applying transverse (shear) and normal (pull-out) loads to the connection. Two 0.625 in. (1.59 cm) diameter Dayton F-42 loop ferrule inserts, one with and the other without reinforcement, were embedded in a 3 ft. x 3 ft. x 8 in. (91.4 cm x 91.4 cm x 20.32 cm), 5000 psi (725.7 kN/m^2) reinforced concrete test panel. During transverse loading, several lengths of A-36 threaded, ductile rods were tested. Many of the connections were also tested under cyclic transverse shear loading until fatigue failure occurred. Strain gages were placed at various locations on the insert, the ductile rod and the reinforcing material. Displacement and strain data were taken and evaluated in order to determine the stiffnesses and load histories for the push-pull connection.

A spring supported simple numerical beam model with 24 beam elements was used to model the ductile rod connection. Parameters of the model were estimated using strain and displacement measurements for the 12 in. (30.5 cm) long ductile rod.

The effectiveness of the connection model was studied using an existing numerical linear frame-panel model of a typical steel frame building. It was shown that the push-pull model was effective in isolating the cladding panel from the underlying building structure. On the other hand, the experimental results suggest that low cycle fatigue failure of the ductile rod under large-

motion conditions was highly likely for the rod length typically employed in practice.

COPIES OF SELECTED PUBLICATIONS FROM SECTION (b) ABOVE

Copies of the following publications are presented below:

6. Goodno, B. J., Craig, J. I., and Zeevaert-Wolff, "Behavior of Architectural Nonstructural Components in the Mexico Earthquake - First Progress Report," Proceedings, First U.S.-Mexico Workshop on 1985 Mexico Earthquake Research, held in Mexico City on November 16-18, 1986, pp. 85-90, published by Earthquake Engineering Research Institute (EERI), April 1987.

7. Goodno, B. J., Craig, J. I., and Zeevaert-Wolff, "Behavior of Architectural Nonstructural Components in the Mexico Earthquake - Second Progress Report," Proceedings, 2ND U.S.-Mexico Workshop on 1985 Mexico Earthquake Research, held in Mexico City on November 5-7, 1987, 6 pages, published by Earthquake Engineering Research Institute (EERI), November 1987.

13. Goodno, B. J., Craig, J. I., and Zeevaert-Wolff, "Behavior of Architectural Nonstructural Components in the Mexico Earthquake - Third Progress Report," 7 pages, Earthquake Engineering Research Institute (EERI), May 1988.

18. Goodno, B. J., Craig, J. I., and Zeevaert-Wolff, "Behavior of Architectural Nonstructural Components in the Mexico Earthquake - Final Progress Report," 10 pages, Earthquake Engineering Research Institute (EERI), January 1989.

19. Goodno, B. J., Craig, J. I., and Zeevaert Wolff, A., "Behavior of Heavy Cladding Components in the Mexico Earthquake," Earthquake Spectra, EERI, Vol. 5, No. 1, February 1989, pp. 195-222.

1st Prog. Rep.

BEHAVIOR OF ARCHITECTURAL NONSTRUCTURAL COMPONENTS IN THE MEXICO EARTHQUAKE

U.S. Principal Investigators: Barry J. Goodno
James I. Craig
Georgia Institute of Technology
Atlanta, Georgia 30332

Mexican Collaborator: Adolfo Zeevaert Wolff
Torre Latino Americana 2506
06007 Mexico Centro, D.F.

Date Prepared: April 7, 1987

Project Objectives. The research program is aimed at acquiring invaluable data on nonstructural performance in a recent major earthquake. The primary objective of this effort is to develop a functional understanding of the role of nonstructural cladding in the structural performance of buildings under severe ground motion conditions. Specifically, this concerns the actual and potential contributions of cladding to the lateral stiffness under normal loading conditions and the potential energy dissipation (damping) that can be developed under severe loading conditions. Secondary objectives involve assessing the appropriateness of existing code provisions related to cladding and identifying potential modifications or extensions that would provide for improved performance.

Project Scope. The research program consists of a combined field study of building cladding performance during the 1985 Mexico earthquake and supporting analytical and experimental studies of cladding connection systems typical of practice in Mexico City. This research effort is broken down into three phases:

1. Phase I: Nonstructural damage survey and evaluation for selected buildings in Mexico City.
2. Phase II: Laboratory testing of cladding connections representative of Mexican practice.
3. Phase III: Analytical evaluation of case study buildings for cladding-structure interaction effects.

Laboratory testing and analytical studies are currently underway for cladding connection designs typical of U.S. practice. This study of the behavior of architectural cladding systems in the Mexico Earthquake is intended to complement on-going research to the greatest extent possible. The data gathering, laboratory experimental, and analytical phases described above are designed to provide a balanced and coordinated attack on the problem of nonstructural performance in earthquakes and to extraction of as much useful information as possible for the benefit of both Mexico and the United States.

Summary of Findings to Date. The summary of findings to date is arranged in three parts that cover each of the three principal phases of the research project.

Phase I - Damage Survey in Mexico City: The first effort initiated under the grant has been to conduct a survey of the damage to cladding during the

Mexico Earthquake. The principal responsibility for this phase has been handled by Dr. Zeevaert-Wolff in Mexico City, and the work was initiated shortly before the November 1986 meeting.

In the months following the earthquake, relatively little attention was directed to examining or studying the damage experienced by cladding, since the principal concern was clearly to deal with the major structural failures, or where damage was light, to get the buildings back into service as quickly as possible. As a result, our study was initiated with relatively little information or information that was incidental to other surveys and studies. Fortunately, Dr. Zeevaert-Wolff was able to witness the earthquake from the 25th floor of the Torre Latino Americana and immediately set about photographing and surveying the resulting damage. This information, along with his personal involvement in the subsequent rebuilding phases, has been the principal source of information for Phase I of our study.

All the principals spent several days in late 1986 in Mexico City reviewing the available information and touring selected buildings. This meeting provided the initial direction for the survey and established the evaluation criteria. Principal areas of interest were:

(a) Buildings with relatively extensive precast or GFRC cladding systems,
(b) Structures in the 10-20 story range,
(c) Buildings for which both structural design and as-built information was available, or for which on-site inspections could reveal the latter information.

The last requirement has ruled out several promising buildings and many buildings that have already been stripped of their cladding.

A preliminary report covering examination of 25 buildings meeting most or all of these requirements has been completed. This list has been carefully reviewed and reduced to 12 structures that meet all the conditions. From these 12, a working list of 4 buildings has been assembled and these will form the basis for more detailed evaluations. In addition to the damage surveys, the Phase I study includes a review of the cladding design practice and representative examples of connection designs in the Mexico City region.

Phase II - Laboratory Testing of Cladding Connections: Work under this phase will begin during the second quarter of 1987 after the candidate connection designs from Mexican practice have been identified. Work to date has involved the modification and refinement of the test facilities to accommodate the planned tests.

At this time the testing facility and data acquisition system are fully operational. The facility is designed to handle a variety of inserts that have been cast into a test slab measuring 3 ft. (914 mm) square by up to 8 in. (203 mm) thick. The slab is fixed to a reinforced test bed using up to 8 tie rods and grouting. The various load conditions can be applied by means of conventional multi-axis servo-controlled hydraulic actuators. The present fixture has been modified to allow the following combinations of loading:

(a) Direct pullout (normal to slab),
(b) Single axis inplane shear load (parallel to slab which simulated gravity or inplane lateral or racking loads),
(c) Single axis bending (about an axis parallel to slab which simulates bending loads),
(d) Combinations of (b) and (c).

The current arrangement does not allow application of torsion loads (moment loads about an axis normal to the slab) which would simulate the loading due to inplane racking motion of the building face.

The data acquisition system consists of an IBM PC/XT with associated hardware and software that can be used to monitor and control each test. Monitoring functions are handled by multi-channel strain and voltage measuring instruments interfaced via an IEEE-488 bus, and control is accomplished either manually or with custom-built D/A converter systems. All programming for testing and analysis is handled in Turbo Pascal or through standard software (e.g. Lotus).

Pullout tests on both wedge and weld plate type inserts commonly used in US construction are currently being completed under separate sponsorship. This program has provided the opportunity to develop and refine the specimen design, fabrication and testing procedures that will be employed in the current program.

Phase III - Analytical Studies of Cladding and Connections: The major activities in the analytical program to date have been concentrated in two principal areas: (1) refinement of both the analytical models for heavy cladding and the associated computer programs developed in past studies; and (2) assemblage of finite element models for the cladding connection inserts to support the laboratory experimental program (Phase II).

Refinement of Cladding Models: Analytical studies are being carried out on a one bay, one story frame-panel model. The model consists of a two dimensional representation of the frame with attached rigid cladding panels and elastic spring connection elements. This model was used in previous studies to predict localized static and linear dynamic behavior of the frame-panel assembly. The existing analytical model is currently being refined to include connection nonlinearities, hysteretic behavior and damping effects. Experimental test results for the cladding connections from Phase II are available for use in redefining these properties. The effect of the sealant between the panels, especially on damping, is also to be included in the analytical model. The possibility of panel-to-panel contact during severe interstory motions was also considered but was found to be of concern at the building corners only. Finally, in a separate study, the localized panel-frame model is being reassembled in the form of a three-dimensional superelement model. Full advantage is taken of symmetry in the model so that more model degrees of freedom can be used to consider a wide variety of boundary conditions, panel geometries and loadings.

Results obtained from the localized panel model will be used in the overall model of the case study building in subsequent studies outlined below. Although the present analytical model was developed for a U.S. case study building, it will be used as well, with appropriate modifications, in the evaluation of a sample building in Mexico City to be selected at the conclusion of Phase I.

<u>Finite Element Models of Connection Inserts</u>: Two finite element model for wedge and plate inserts embedded in concrete slabs have been developed. These models will be used in analytical studies in which the stresses and displacements in the inserts and in the surrounding concrete will be examined under various loading conditions in the linear range, i.e., when the applied loadings are small. Models developed thus far assume linear material behavior for concrete, but will be modified later to incorporate nonlinear effects. Once complete, these models will be used to predict insert behavior up to failure. Experimental data from pull-out tests conducted on insert specimens is currently being used to verify the accuracy of the finite element models, after which other loading conditions not simulated in laboratory experiments will be considered.

The model for the embedded wedge insert consists of 873 nodes and 1533 elements (see Fig. 1). Because of symmetry of both the structure and loadings, only one half of the concrete slab containing the insert is modeled. The insert itself is represented by 129 quadrilateral and triangular thin shell (plate) elements and 12 brick and wedge type solid elements (Figs. 2, 3). The surrounding concrete is modeled by brick, wedge, and tetrahedral solid elements. For the embedded plate insert, only one quarter of the model is represented due to symmetry. The model contains 910 nodes and is comprised of 819 solid elements of which 59 are used to define the insert. Boundary conditions for both models consist of restraints along bottom edges on the periphery of the slabs. Restraints are also specified on the middle faces to account for symmetry. Both pull out and shear loads are applied to the models.

<u>Summary of Planned Activities for Remainder of Project</u>. Phase I tasks are nearing completion and a meeting has been tentatively scheduled at the end of April in Atlanta to discuss the preparation of the report describing the damage survey conducted in Mexico City. It remains to select one or two Mexico City buildings from the current list of twelve buildings whose cladding performance has been documented in the 1985 earthquake for more in depth study during the experimental and analytical phases of the overall project. The provisions of past and present Mexico City codes related to design and attachment of heavy claddings will also be reviewed to complete Phase I activities.

Several heavy cladding connections representative of Mexican practice will be selected from the damage survey for laboratory testing during Phase II. It is expected that 12 to 14 specimens will be fabricated which are compatible with the current test facility. The fabrication of these specimens by a local precast firm and subsequent testing is expected to be carried out over the next 12 to 15 months.

Finally, the analytical studies in Phase III will be concerned with continued development of the superelement models of the cladding subsystem and further refinement of the finite element models of the connection inserts. The cladding subsystem models will be incorporated into existing models of the U.S. case study building for further more refined analysis of that structure before being used to study the building in Mexico City identified in the Phase I survey. Results of all analytical investigations will be used to reevaluate applicable provisions of both U.S. and Mexico codes related to heavy cladding systems.

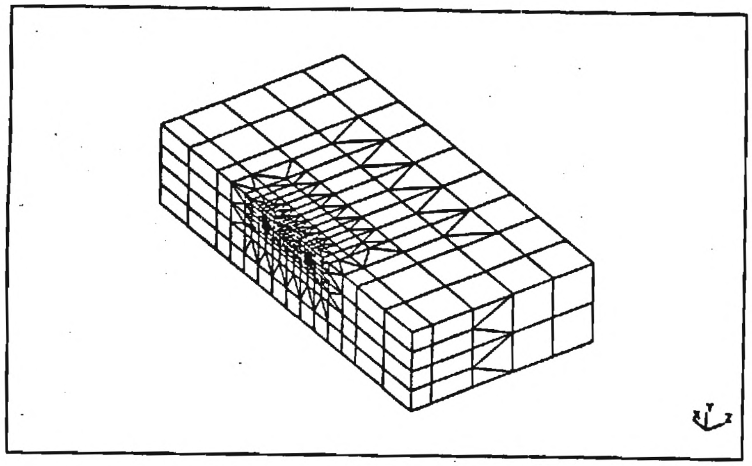

Fig. 1- Symmetry Model of Concrete Slab and Embedded Wedge Insert Connection

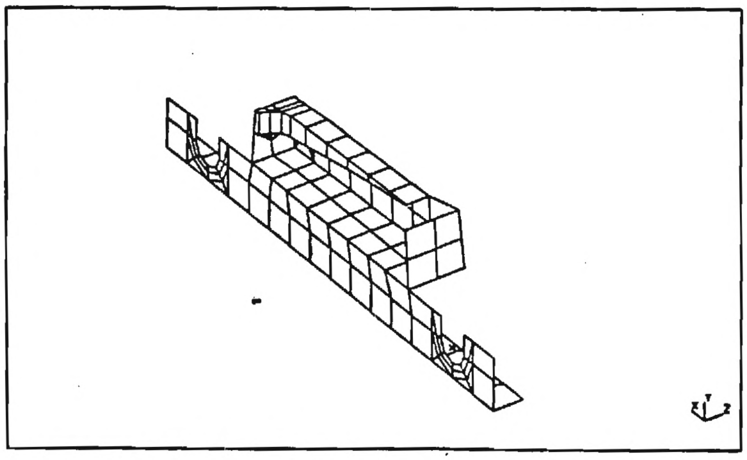

Fig. 2- Symmetry Model of Wedge Insert

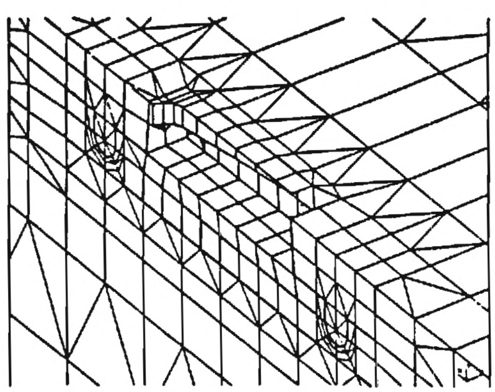

Fig. 3- Close-up View of Wedge Insert in Concrete Slab

BEHAVIOR OF ARCHITECTURAL NONSTRUCTURAL
COMPONENTS IN THE MEXICO EARTHQUAKE
Second Progress Report

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Project Objectives. The research program is aimed at acquiring invaluable data on nonstructural performance in a recent major earthquake. The primary objective of this effort is to develop a functional understanding of the role of nonstructural cladding in the structural performance of buildings under severe ground motion conditions. Specifically, this concerns the actual and potential contributions of cladding to the lateral stiffness under normal loading conditions and the potential energy dissipation (damping) that can be developed under severe loading conditions. Secondary objectives include assessing the appropriateness of existing code provisions related to cladding and identifying potential modifications or extensions that would lead to improved performance.

Project Scope. The research program consists of a combined field study of building cladding performance during the 1985 Mexico earthquake and supporting analytical and experimental studies of cladding connection systems typical of practice in Mexico City. This research effort is broken down into three phases:

1. Phase I: Nonstructural damage survey and evaluation for selected buildings in Mexico City.
2. Phase II: Laboratory testing of cladding connections representative of Mexican practice.
3. Phase III: Analytical evaluation of case study buildings for cladding-structure interaction effects.

Laboratory testing and analytical studies are currently underway for cladding connection designs typical of U.S. practice. This study of the behavior of architectural cladding systems in the Mexico Earthquake is intended to complement on-going research to the greatest extent possible. The data gathering, laboratory experimental, and analytical phases described above are designed to provide a balanced and coordinated attack on the problem of nonstructural performance in earthquakes and extraction of as much useful information as possible for the benefit of both Mexico and the United States.

Summary of Findings to Date. The summary of findings to date is arranged in three parts that cover each of the three principal phases of the research project. This summary is a continuation and update of the First Progress Report which was prepared in April 1987.

Phase I - Damage Survey in Mexico City: The first effort initiated under the grant has been to conduct a survey of the damage to cladding during the Mexico Earthquake. The principal responsibility for this phase has been handled by Dr. Zeevaert-Wolff in Mexico City, and the work was initiated shortly before the November 1986 meeting.

In the months following the earthquake, relatively little attention was directed to examining or studying the damage experienced by cladding, since the principal concern was clearly to deal with the major structural failures, or where damage was light, to get the buildings back into service as quickly as possible. As a result, our study was initiated with relatively little information or information that was incidental to other surveys and studies. Fortunately, Dr. Zeevaert-Wolff was able to witness the earthquake from the 25th floor of the Torre Latino Americana and immediately set about photographing and surveying the resulting damage. This information, along with his personal involvement in the subsequent rebuilding phases, has been the principal source of information for Phase I of our study.

All the principals spent several days in late 1986 in Mexico City reviewing the available information and touring selected buildings. This meeting provided the initial direction for the survey and established the evaluation criteria. Principal areas of interest were:

(a) Buildings with relatively extensive precast or GFRC cladding systems,
(b) Structures in the 10-20 story range,
(c) Buildings for which both structural design and as-built information was available, or for which on-site inspections could reveal the latter information.

The last requirement has ruled out several promising buildings and many buildings that have already been stripped of their cladding.

A Phase I report covering examination of 25 buildings meeting most or all of these requirements has been completed. This list was then carefully reviewed and reduced to 12 structures that meet all the conditions. From these 12, a working list of 4 buildings was assembled and relatively complete architectural and structural drawings were obtained. One of these buildings has been selected for detailed study, and work is currently underway to model both the structure and the cladding as a part of Phases II and III. In addition to the damage surveys, the Phase I study also includes a review of the cladding design practice and representative examples of connection designs in the Mexico City region.

Phase II - Laboratory Testing of Cladding Connections: The Phase I study has identified several types of cladding connections that appear to be widely used in practice. Of these, the welded insert and its variations are the most common for relatively heavy cladding, but direct attachment via reinforced grouting is frequently employed for lighter weight cladding. No examples of bolted inserts were observed. As a result, the Phase II tests are being designed to explore the performance of:

* Welded connections using embedded weld plates that are typical of those

actually employed on the building selected for detailed modeling,

* Several types of reinforced grout connections.

At this time the testing facility and data acquisition system are fully operational. The facility is designed to handle a variety of inserts that have been cast into a test slab measuring 3 ft. (914 mm) square by up to 8 in. (203 mm) thick. The slab is fixed to a reinforced test bed using up to 8 tie rods and grouting. The various load conditions can be applied by means of conventional multi-axis servo-controlled hydraulic actuators. The present fixture has been modified to allow the following combinations of loading:

(a) Direct pullout (normal to slab),
(b) Single axis inplane shear load (parallel to slab which simulated gravity or inplane lateral or racking loads),
(c) Single axis bending (about an axis parallel to slab which simulates bending loads),
(d) Combinations of (b) and (c).

The current arrangement does not allow application of torsion loads (moment loads about an axis normal to the slab) which would simulate the loading due to inplane racking motion of the building face. A typical detail of the fixture showing the arrangement for applying loading cases (b) and (c) above is given in Figure 1.

The data acquisition system consists of an IBM PC/XT with associated hardware and software that can be used to monitor and control each test. Monitoring functions are handled by multi-channel strain and voltage measuring instruments interfaced via an IEEE-488 bus, and control is accomplished either manually or with custom-built D/A converter systems. All programming for testing and analysis is handled in Turbo Pascal or through standard software (e.g. Lotus).

Pullout tests on both wedge and weld plate type inserts commonly used in US construction are currently being completed under separate sponsorship. This program has provided the opportunity to develop and refine the specimen design, fabrication and testing procedures that will be employed in the current program.

<u>Phase III - Analytical Studies of Cladding and Connections</u>: The major activities in the analytical program to date have been concentrated in four principal areas: (1) preparation of the computer model of the Mexican case study building; (2) extension of the analytical and experimental studies of wedge insert and embedded plate connections to include ductile rod systems; (3) continued development of the superelement model of one cladding panel and its supporting connections and framework; and (4) assemblage of detailed finite element models for the cladding connection inserts to support the laboratory experimental program (Phase II). Each of these topic areas is discussed separately below.

<u>Mexican Case Study Building</u>: The case study building has been selected and the structural drawings are currently under review. The building will be studied to determine the possible role which the heavy precast concrete exterior facade played in its response during the 1985 earthquake. The

analysis will include the main structural components as well as the nonstructural cladding which experienced some damage during the earthquake. The analytical model will be subjected to the ground motion experienced during the earthquake. The objective of this analysis will be to study the force levels and to explain the damage observed during the earthquake, particularly to the cladding components.

The more refined models of the cladding developed in past studies will be altered as needed and integrated into the overall model of the concrete frame structure. The cladding models will be based on the two-dimensional frame panel model which is being refined to include both connection nonlinearities and cladding damping effects. Three-dimensional cladding models and superelement models which were developed recently will also be used.

Studies of Ductile Rod Connections: This study is an extension of the original research program and involves a modest amount of laboratory testing along with analytical evaluation of a cladding connection system which is in widespread use in California. In the laboratory testing, a Dayton Superior 5/8 inch N-42 loop ferrule insert and a 12 inch long, 5/8 inch diameter, A-36 rod will be tested in direct pullout and single axis inplane shear. Strain gages will be placed on the neck of the loop insert, and on the ductile rod and the reinforcing bar. Test data will be compared to results of previous programs. From the test data, the hysteretic behavior of the connection system will be studied and stiffnesses calculated for use in the finite element model of the cladding system. Performance of the overall building models with different cladding connection systems (i.e., wedge insert, embedded plate, and ductile rod) will be compared.

Superelement Model for Cladding: A superelement model for a representative portion of a heavyweight cladding system has been developed for use in the overall building model (see Figure 2). The model includes the precast panel, the clip angle attachments, and the supporting spandrel members from the exterior frame. By condensing out the extraneous interior degrees of freedom from the model, only the essential freedoms on the periphery are retained for use in the dynamic analysis of the overall structure. Using backsubstitution, the connection and member forces as well as the distortions and stresses in the precast panel will be determined at some specified location on the exterior facade at the completion of the lateral force analysis.

Finite Element Models of Connection Inserts: Finally, to complement the experimental investigation of the behavior of the different inserts embedded in concrete slabs and subjected to various loading conditions, finite element models were developed for the plate and the wedge inserts. These moderate-size models were constructed using a relatively fine mesh in the region of the insert itself, combined with a progressively coarser mesh to model the surrounding concrete, taking advantage of symmetry where appropriate to minimize the modeling effort and the analysis cost.

In the models developed initially, one set of nodes was used for the steel/concrete interface in both the models. But the wedge insert model has now been modified so that two coincident sets of nodes are used along the interface, one for the steel elements representing the insert and the other for concrete. Similar modifications are being implemented for the plate insert model also. This facilitates the consideration of varying degrees of coupling between steel and concrete. When the two sets of nodes are connected by a rigid link, complete coupling between steel and concrete is implied. But if not all nodal degrees of freedom of the nodes of one set are rigidly linked to the corresponding nodal degrees of freedom of the other set, only partial coupling is realized. In this case, the steel and concrete along the interface can have different amounts of deformation in those degrees of freedom that are not linked. It is also possible to model flexible links between the two sets of nodes by coupling these sets through springs instead of rigid connections. Although such a representation of the steel/concrete interface by two sets of nodes increases the size and the complexity of the model, it provides a certain amount of flexibility in studying some imperfect bonding conditions that might occur in practice.

Experimental data available to date for the wedge insert from pullout tests conducted on several specimens have been compared to the finite element model predictions. Any correlation between analysis and experiment is complicated by the fact that different types of behavior were observed in different insert specimens during the pullout tests. For one of the specimens that showed nearly linear behavior over the loading range employed in the tests, excellent agreement was found between the test data and linear finite element analysis with complete interface coupling, at least for those locations where strains were measured. But the other specimens were found to exhibit significant nonlinear behavior in the form of a change in slope of the load-strain curve for load values above a certain level. In fact, for one of the specimens, changes in both the magnitude and the sign of the slope were observed at one of the measurement locations. If experimental errors are discounted, such behavior points up the differences between various specimens themselves, which in turn is an indication of the high variability or nonuniformity that may be expected in crucial aspects such as bonding.

The observed nonlinearities may be caused by, among other things, nonlinear material behavior of concrete due to factors such as exceeding the usually small tensile strength at various locations around the insert. But another cause that is more likely involves the debonding of steel from concrete at different interface regions. The linear finite element model is currently being modified in an effort to understand and investigate the nonlinear response. In the first attempt, gaps are being assumed to exist between steel and concrete along one or more contact faces. As the loads are applied, such gaps may open or close depending on the local deformations. In the case of gap opening, there is no load transmitted from the insert to concrete. On the other hand, if the displacements are such that the gaps tend to close, loads are transmitted in the axial and transverse directions. Coefficients of friction are specified for use in determining the amount of load that can be transmitted in the transverse direction. For load values beyond this amount, sliding is assumed to occur. The MSC/NASTRAN finite element code is being used to model such effects.

By introducing gaps along one or more faces, the possibility of reproducing some of the nonlinear experimental data will be explored. In addition, models involving material nonlinearities will also be considered if necessary. Similar procedures will be used for the plate element model if test data, when available, indicate nonlinear behavior.

BEHAVIOR OF ARCHITECTURAL NONSTRUCTURAL
COMPONENTS IN THE MEXICO EARTHQUAKE
Third Progress Report

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Project Objectives. The research program is aimed at acquiring much-needed data on performance of nonstructural building elements in a recent major earthquake. The primary objective of this study is to develop a functional understanding of the role played by nonstructural cladding elements in the structural performance of buildings under severe ground motion conditions. Specifically, the concern is with both the actual and the potential contributions of cladding to the lateral stiffness under normal loading conditions and the potential energy dissipation (damping) that can be developed under severe loading conditions. Secondary objectives include an assessment of the appropriateness of existing code provisions related to cladding and the identification of potential modifications or extensions that could lead to improved performance.

Project Scope. The research program consists of a combined field study of building cladding performance during the 1985 Mexico earthquake and supporting analytical and experimental studies of cladding connection systems typical of practice in Mexico City. This research effort is broken down into three phases:

1. Phase I: Nonstructural damage survey and evaluation for selected buildings in Mexico City.

2. Phase II: Laboratory testing of cladding connections representative of Mexican practice.

3. Phase III: Analytical evaluation of case study buildings for cladding-structure interaction effects.

Laboratory testing and analytical studies of cladding connection designs typical of U.S. practice have been underway by the authors for several years. The present study of the behavior of architectural cladding systems in the Mexico Earthquake is complementary to this work. The data gathering, laboratory experimental, and analytical phases outlined above are designed to provide a balanced and coordinated attack on the problem of nonstructural performance in earthquakes and to extraction of as much useful information as possible for the benefit of both Mexico and the United States.

Summary of Findings to Date. The summary of findings to date is arranged in three parts that cover each of the three principal phases of the research project. This summary is a continuation and update of the Second Progress Report which was prepared in September 1987.

Phase I - Damage Survey in Mexico City: The first effort initiated under the grant was a survey of the damage to cladding during the Mexico Earthquake. The principal responsibility for this phase was handled by Dr. Zeevaert-Wolff in Mexico City, and the work was initiated shortly before the November 1986 meeting.

A report presenting the results of the Phase I efforts has been drafted and will be the subject of an upcoming EERI Earthquake Spectra journal article prepared by the present authors. The study involved the initial identification of 30 or more buildings that were either known or expected to have experienced noticeable damage to cladding systems. A combination of visual observation, personal contact and review of available damage surveys was used to establish an initial list of 25 candidate buildings. The study process was complicated by the fact that it was initiated more than a year after the earthquake by which time most visible cladding damage to otherwise sound buildings had been repaired or else damaged cladding had been completely removed from severely damaged structures. Nonetheless it was possible to establish selection criteria as follows:

(a) Buildings with relatively extensive precast or GFRC cladding systems, and
(b) Structures in the 10-20 story range, and
(c) Buildings for which both structural design and as-built information was available, or for which on-site inspections could reveal the latter information.

The last requirement was the most important and eventually eliminated several potentially interesting buildings.

The 25 buildings were reviewed and reduced to 12 structures that meet all of the above conditions. Nearly complete architectural and structural drawings were obtained for 4 of these buildings, and one was finally selected for detailed study of both the structure and the cladding as a part of the Phase II and III work. In addition to the damage surveys, results of the Phase I study also include a brief review of cladding design practice and representative examples of connection designs in the Mexico City region.

Phase II - Laboratory Testing of Cladding Connections: The Phase I study identified several types of cladding connections that appear to be widely used in practice. Of these, the weld-plate and its variations are the most common for relatively heavy cladding, but direct attachment via reinforced grouting is often employed for lightweight cladding. Push-pull or ductile rod isolating connections common to West Coast US practice do not appear in common use, and no examples of bolted inserts were observed. As a result, the Phase II tests are being designed to explore the performance of:

* Welded connections using embedded weld plates that are typical of those actually employed on the building selected for detailed modeling,
* Push-pull connections using ductile rods.

Consideration was initially given to testing several types of reinforced grout connections, but difficulties in designing the experimental program coupled with similar difficulties in developing suitable analytical models led to elimination of this class in favor of the push-pull connections which are more widely employed in US practice.

The testing facility and data acquisition system were described in the Second Progress Report and in several recent presentations [1,4,6]. The facility is capable of handling a variety of inserts that have been cast into special concrete test slabs. The fixture is capable of developing the following combinations of loading:

(a) Direct pullout (normal to slab),
(b) Single axis inplane shear load (parallel to slab which simulated gravity or inplane lateral or racking loads),
(c) Single axis bending (about an axis parallel to slab which simulates bending loads),
(d) Combinations of (b) and (c).

The fixture was modified to allow testing of ductile rod connection elements arranged in a push-pull connection design. A typical detail of the fixture showing this type of arrangement is given in Figure 1 in the Second Progress Report.

Testing of the push-pull ductile rod connections has been completed and tests of the weld-plate inserts are currently underway. The push-pull ductile rod connection test program is fully described in a Special Problem Report [3] and will be included in a 9th World Conference on Earthquake Engineering paper [6]. This type of connection design is widely employed in West Coast US practice as a means for providing cladding-structure isolation for inplane motion while at the same time providing adequate out-of-plane resistance to seismic and environmental loads. These connections are typically used for two of the panel connections and rigid inplane connections are used at the remaining two locations. Under strong motion, the connections allow large inplane movement between the cladding and the supporting building structure.

Analytical models and experimental tests carried out under Phase II have confirmed the basic behavior assumed for these designs. Measured stresses and deflections agreed well with simple linear elastic beam models for the ductile rods. The beam models were also able to accurately predict the onset of inelastic behavior at large levels of transverse displacement. However, the most significant result of these tests was the observation of low-cycle fatigue failure of the ductile rod. Various lengths of ductile rod connections typical of common practice were subjected to systematically increasing cycles of transverse (lateral) displacements with no axial load applied. In all cases tested (8 total), each of the rods experienced low-cycle fatigue cracking at one or both roots (panel end and building end) for displacement amplitudes up to but not exceeding typical (UBC) code provisions for interstory drift. In addition, in one half of the cases complete fracture occurred at one or the other end within 25 displacement cycles. Taken together, these observations confirm the accuracy of both the elastic and inelastic static connection design models, but they strongly indicate that a static analysis is inadequate for predicting the behavior during strong motion conditions. While it seems unlikely that virgin connections will fracture under a single earthquake, it appears likely that some connections will fail after exposure to several moderate or strong earthquakes. As noted below, simple connection failure models based on these experimental results are being incorporated into analytical building models which will be subjected to different earthquake records.

The weld-plate connection test program is currently in progress. Connection specimens and test fixtures have been designed and the preliminary tests are underway. Connection specimens representing all major types of cladding connections employed on the Phase I study building are being investigated. Particular interest is being given to connections typical of those used at external vertical corners and at thin edges and corners of individual panels.

<u>Phase III - Analytical Studies of Cladding and Connections</u>: As noted in the Second Progress Report, the major activities in the analytical program to date have been concentrated in four principal areas: (1) preparation of the computer model of the Mexican case study building; (2) extension of the analytical and experimental studies of wedge insert and embedded plate connections to include ductile rod systems; (3) continued development of the superelement model of one cladding panel and its supporting connections and framework; and (4) assemblage of detailed finite element models for the cladding connection inserts to support the laboratory experimental program (Phase II). Each of these topic areas is discussed separately below.

<u>Mexican Case Study Building</u>: The case study building has been selected, the structural drawings reviewed, and a preliminary 3D computer model of the structure prepared. The building is being studied to determine the possible role which the heavy precast concrete exterior facade played in its response during the 1985 earthquake. The analytical model includes the main structural components as well as the nonstructural cladding which experienced some damage during the earthquake. The computer model will be subjected to the ground motion experienced during the earthquake. The objective of this analysis will be to study the force levels and to explain the damage observed during the earthquake, particularly to the cladding components.

The more refined models of the cladding developed in past studies [2] will be altered as needed and integrated into the overall model of the concrete frame structure as the study progresses. The cladding models will be based on the two-dimensional frame panel model as well as the three dimensional cladding models and superelement models developed in earlier investigations.

<u>Studies of Ductile Rod Connections</u>: As noted above under a description of the Phase II work, this portion of the study represents an extension to the original scope of work on the research project. A report [3] based on this work presents the results of the investigation of the mechanical performance of push-pull (ductile rod) connections typically employed on the West Coast of the United States for earthquake isolation of architectural precast cladding panels. The tests were carried out on specially designed laboratory specimens using a fixture that was capable of applying transverse (shear) and normal (pull-out) loads to the connection. Two 0.625 in. (1.59

cm) diameter Dayton F-42 loop ferrule inserts, one with and the other without reinforcement, were embedded in a 3 ft. x 3 ft. x 8 in. (91.4 cm x 91.4 cm x 20.32 cm), 5000 psi (725.7 kN/m^2) reinforced concrete test panel. During transverse loading, several lengths of A-36 threaded, ductile rods were tested. Many of the connections were also tested under cyclic transverse shear loading until fatigue failure occurred. Strain gages were placed at various locations on the insert, the ductile rod and the reinforcing material. Displacement and strain data were taken and evaluated in order to determine the stiffnesses and load histories for the push-pull connection.

A spring supported simple numerical beam model with 24 beam elements was used to model the ductile rod connection. Parameters of the model were estimated using strain and displacement measurements for the 12 in. (30.5 cm) long ductile rod.

The effectiveness of the connection model was studied using an existing numerical linear frame-panel model of a portion of a typical steel frame building. It was shown that the push-pull model was effective in isolating the cladding panel from the underlying building structure. On the other hand, the experimental results suggest that low cycle fatigue failure of the ductile rod under large-motion conditions was highly likely for the rod length typically employed in practice (see discussion under Phase II work above). The possibility of fatigue failure will be explored in future studies of the overall building model with heavyweight cladding panels supported by ductile rod connections.

Superelement Model for Cladding: A superelement model for a representative portion of a heavyweight cladding system has been developed for use in the overall building model (see Figure 2 in the Second Progress Report). The model includes the precast panel, the clip angle attachments, and the supporting spandrel members from the exterior frame. By condensing out the extraneous interior degrees of freedom from the model, only the essential freedoms on the periphery are retained for use in the dynamic analysis of the overall structure. Using backsubstitution, the connection and member forces as well as the distortions and stresses in the precast panel will be determined at some specified location on the exterior facade at the completion of the lateral force analysis. Results of this investigation will be presented in several papers at the 9th World Conference on Earthquake Engineering [7,8].

Finite Element Models of Connection Inserts: Finally, to complement the experimental investigation of the behavior of the different inserts embedded in concrete slabs and subjected to various loading conditions, finite element models were developed for the plate and the wedge inserts [5]. These moderate-size models were constructed using a relatively fine mesh in the region of the insert itself, combined with a progressively coarser mesh to model the surrounding concrete, taking advantage of symmetry where appropriate to minimize the modeling effort and the analysis cost.

In the models developed initially, one set of nodes was used for the steel/concrete interface in both the models. But the wedge insert model was later modified so that two coincident sets of nodes were used along the interface, one for the steel elements representing the insert and the other for concrete. Similar modifications are being implemented for the plate insert model also. This facilitates the consideration of varying degrees of coupling between steel and concrete. When the two sets of nodes are connected by a rigid link, complete coupling between steel and concrete is implied. But if not all nodal degrees of freedom of the nodes of one set are rigidly linked to the corresponding nodal degrees of freedom of the other set, only partial coupling is realized. In this case, the steel and concrete along the interface can have different amounts of deformation in those degrees of freedom that are not linked. It is also possible to model flexible links between the two sets of nodes by coupling these sets through springs instead of rigid connections. Although such a representation of the steel/concrete interface by two sets of nodes increases the size and the complexity of the model, it provides a certain amount of flexibility in studying some imperfect bonding conditions that might occur in practice.

Experimental data available to date for the wedge insert from pullout tests conducted on several specimens have been compared to the finite element model predictions. These efforts are continuing. Any correlation between analysis and experiment is complicated by the fact that different types of behavior were observed in different insert specimens during the pullout tests. For one of the specimens that showed nearly linear behavior over the loading range employed in the tests, excellent agreement was found between the test data and linear finite element analysis with complete interface coupling, at least for those locations where strains were measured. But the other specimens were found to exhibit significant nonlinear behavior in the form of a change in slope of the load-strain curve for load values above a certain level. In fact, for one of the specimens, changes in both the magnitude and the sign of the slope were observed at one of the measurement locations. If experimental errors are discounted, such behavior points up the differences between various specimens themselves, which in turn is an indication of the high variability or nonuniformity that may be expected in crucial aspects such as bonding.

The observed nonlinearities may be caused by, among other things, nonlinear material behavior of concrete due to factors such as exceeding the usually small tensile strength at various locations around the insert. But another cause that is more likely involves the debonding of steel from concrete at different interface regions. The linear finite element model is currently being modified in an effort to understand and investigate the nonlinear response. In the first attempt, gaps are being assumed to exist between steel and concrete along one or more contact faces. As the loads are applied, such gaps may open or close depending on the local deformations. In the case of gap opening, there is no load transmitted from the insert to concrete. On the other hand, if the displacements are such that the gaps tend to close, loads are transmitted in the axial and transverse directions. Coefficients of friction are specified for use in determining the amount of load that can be transmitted in the transverse direction. For load values beyond this amount, sliding is assumed to occur. The MSC/NASTRAN finite element code is being used to model such effects.

By introducing gaps along one or more faces, the possibility of reproducing some of the nonlinear experimental data has been explored. These efforts have been partially successful to date, showing that the appropriate boundary conditions for several of the specimens lie somewhere between the unbonded and fully bonded states over at least a portion of their full range of behavior. In future studies, models involving material nonlinearities will also be considered if necessary. Similar procedures will be used for the plate element model if test data, when available, indicate nonlinear behavior.

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BEHAVIOR OF ARCHITECTURAL NONSTRUCTURAL
COMPONENTS IN THE MEXICO EARTHQUAKE
Final Progress Report

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Project Objectives. The research program is aimed at acquiring much-needed data on performance of nonstructural building elements in a recent major earthquake. The primary objective of this study is to develop a functional understanding of the role played by nonstructural cladding elements in the structural performance of buildings under severe ground motion conditions. Specifically, the concern is with both the actual and the potential contributions of cladding to the lateral stiffness under normal loading conditions and the potential energy dissipation (damping) that can be developed under severe loading conditions. Secondary objectives include an assessment of the appropriateness of existing code provisions related to cladding and the identification of potential modifications or extensions that could lead to improved performance.

Project Scope. The research program consists of a combined field study of building cladding performance during the 1985 Mexico earthquake and supporting analytical and experimental studies of cladding connection systems typical of practice in Mexico City. This research effort is broken down into three phases:

1. Phase I: Nonstructural damage survey and evaluation for selected buildings in Mexico City.

2. Phase II: Laboratory testing of cladding connections representative of Mexican practice.

3. Phase III: Analytical evaluation of case study buildings for cladding-structure interaction effects.

Laboratory testing and analytical studies of cladding connection designs typical of U.S. practice have been underway by the authors for several years. The present study of the behavior of architectural cladding systems in the Mexico Earthquake is complementary to this work. The data gathering, laboratory experimental, and analytical phases outlined above are designed to provide a balanced and coordinated attack on the problem of nonstructural performance in earthquakes and to extraction of as much useful information as possible for the benefit of both Mexico and the United States.

Summary of Findings to Date. The summary of findings to date is arranged in three parts that cover each of the three principal phases of the research project. This summary is a continuation and update of the Third Progress Report which was prepared in May 1988 [8; see also 1,2].

Phase I - Damage Survey in Mexico City: The first effort initiated under the grant was a survey of the damage to cladding during the Mexico Earthquake. The principal responsibility for this phase was handled by Dr. Zeevaert-Wolff in Mexico City, and the work was initiated shortly before the November 1986 meeting.

A paper presenting the results of the Phase I efforts has been prepared by the present authors and published in EERI's Earthquake Spectra [13]. The study involved the initial identification of 30 or more buildings that were either known or expected to have experienced noticeable damage to cladding systems. A combination of visual observation, personal contact and review of available damage surveys was used to establish an initial list of 25 candidate buildings meeting the following criteria:

(a) Buildings with relatively extensive precast or GFRC cladding systems, and
(b) Structures in the 10-20 story range, and
(c) Buildings for which both structural design and as-built information was available, or for which on-site inspections could reveal the latter information.

The last requirement was the most important and eventually eliminated several potentially interesting buildings. The 25 buildings were reviewed and reduced to 12 structures that meet all of the above conditions. Nearly complete architectural and structural drawings were obtained for 4 of these buildings, and one was finally selected for detailed study of both the structure and the cladding as a part of the Phase II and III work. In addition to the damage surveys, results of the Phase I study also include a brief review of cladding design practice and representative examples of connection designs in the Mexico City region.

Phase II - Laboratory Testing of Cladding Connections: The Phase I study identified the weld-plate and its variations as being widely used for relatively heavy cladding, but direct attachment via reinforced grouting is often employed for lightweight cladding. Push-pull or ductile rod isolating connections common to West Coast U.S. practice do not appear in common use, and no examples of bolted inserts were observed in the limited sample of buildings studied. The building selected on the basis of Phase I findings for detailed study and structural modeling employed weld-plate inserts in both the structure and the cladding panels. As a result, the Phase II tests were designed to study the performance of:

- Welded connections using embedded weld plates typical of those actually employed on the study building, and
- Push-pull connections using ductile rods.

Consideration was given to testing several types of reinforced grout connections, but difficulties in designing the experimental program coupled with similar difficulties in developing suitable analytical models led to elimination of this class in favor of the push-pull connections which are more widely employed in U.S. practice.

The testing facility and data acquisition system were described in the Second Progress Report and in other publications [1,2,5,8,11]. The facility is capable of handling a variety of inserts that have been cast into simple concrete test slabs. The fixture, which is shown in Fig. 1, is capable of developing combinations of loading including:

(a) direct pullout (normal to slab),
(b) single-axis inplane shear load (parallel to slab which simulates gravity or inplane lateral or racking loads),
(c) single-axis bending (about an axis parallel to slab which simulates bending loads due too connection eccentricity),
(d) combinations of (b) and (c).

Ductile Rod Tests: Testing of the push-pull ductile rod connections has been completed. The push-pull ductile rod connection test program has been fully described elsewhere [5,11]. This type of connection design is widely employed in West Coast U.S. practice as a means for providing cladding-structure isolation for inplane motion while at the same time providing adequate out-of-plane resistance to seismic and environmental loads. These connections are typically used for two of the panel connections and rigid inplane connections are used at the remaining two locations. Under strong motion, the connections allow large inplane movement between the cladding and the supporting building structure. They were included in the present program because of the potential applicability to Mexican practice.

The basic test fixture was modified to accommodate the panel insert (threaded loop ferrule), the connection element (threaded rod), and the building attachment (oversized hole). Strain gages were placed at critical locations on the insert, reinforcing members and the ductile rod itself. Inplane (shear) and normal (pullout) displacement measurements across the connection were taken to determine the stiffnesses and load histories for both the connection and the insert.

Elastic limits of the connection under inplane (shear) loading for various rod lengths were measured by applying successively greater cyclic displacements across the connection. Rods bending strains showed ductile behavior with well-defined elastic limits while strains in the insert remained relatively small and elastic. Relative inplane displacement across the connection also exhibited clear ductile behavior (Fig. 2). The test results are summarized in Fig. 3 by superposing the measured limit loads and displacements for various rod lengths on a typical set of design curves. It can be seen that the measured deflection limits are approximately two times the design values (conservative margin) while the force limits fall nearly on the design curves.

The overall connection ductility was measured by applying 10 repetitive cycles of inplane (shear) displacements across the connection for successively increasing levels of displacement until failure occurred. Approximately half of the connections tested eventually exhibited slip of the rod in the oversized hole which simulated the typical building attachment, even though the anchoring nuts were securely tightened at the outset. The general effect of this behavior was to extend the number of cycles to failure by effectively decreasing the connection stiffness. The desirability of this effect in practice is questionable, but it can be prevented by tack-welding the washers.

The push-pull connections exhibited a clear low-cycle fatigue behavior with failure of the rods due to bending induced fracture occurring after 47 to 90 cycles (Fig. 4). All failures occurred at displacements of less than +/-2 in. (51 mm) which is less than the UBC interstory drift requirement for an 11 ft. (3.35 m) story height. On the basis of these tests it appears that the push-pull connection exhibits the intended and desirable ductile behavior but may be vulnerable to low-cycle fatigue failure at numbers of cycles well within what might be expected over several moderate earthquakes or for a particular earthquake such as the Mexico 1985 which provides strong dynamic excitation of certain types of buildings.

The pullout capacity of the loop ferrule insert itself was measured by application of cyclic tensile pullout (normal) forces. Both specimens tested exhibited good elastic behavior to almost 4 times the specified working load. A typical shear cone failure occurred in both instances, and the reinforcing elements were effective in retaining the insert and in maintaining a minimal level of connection integrity.

Taken together, these observations confirm the accuracy of both the elastic and inelastic static connection design models, but they strongly indicate that a static analysis alone is inadequate for predicting the earthquake behavior. While it is doubtful that virgin connections will fracture under a single earthquake, it appears likely that some connections will fail after exposure to several moderate or strong earthquakes. As noted below, simple connection failure models based on these experimental results are being incorporated into analytical building models to be subjected to different earthquake records.

Weld-Plate Tests: The weld-plate connection test program is nearing completion. Connection specimens representing all major types of cladding connections employed on the Phase I study building are being investigated. Particular interest is being given to connections typical of those used at external vertical corners and at thin edges and corners of individual panels.

Recognizing the greater complexity of these designs, the test program has focused on the panel inserts alone without the connection elements present. The present series of tests are concerned with weld-plate inserts fabricated from HR steel to which are welded two or more bent reinforcing bars [13]. (Other tests are studying a studded weld plate). The first phase of the test program has involved application of multi-axis loading (shear, moment and pullout) directly to the insert using the basic test fixture. Response measurements were limited to overall rotations and displacements across the insert-connection interface. No attempt was made to include bonded strain gages on the insert itself because of the need to make weld connections directly to the test insert. The test program begins with purely elastic loading to characterize a elastic response model. This is followed by cyclic loading to successively greater load levels to characterize a nonlinear response model. Testing is continued until insert failure in order to ascertain ultimate capacities and failure modes. Results from these tests will be presented at the Final Workshop scheduled for Mexico City on March 16-18, 1989.

Phase III - Analytical Studies of Cladding and Connections: As summarized in past Progress Reports [1,2,8], the major activities in the analytical program to date have been concentrated in four principal areas: (1) computer simulation and evaluation of the performance of both the structure and the cladding system for the Mexican case study building selected in the Phase I survey; (2) extension of the analytical and experimental studies of wedge insert and embedded plate connections to include both ductile rod systems and inserts representative of Mexican design; (3) continued development of the superelement model of one cladding panel and its supporting connections and framework for a U.S. case study building; and (4) assemblage of detailed finite element models for the cladding connection inserts to support the laboratory experimental program (Phase II). Each of these topic areas is discussed separately below.

Mexican Case Study Building: The case study building is an eleven story reinforced concrete frame structure with waffle floor slabs and heavy precast concrete facade on the street face of the building only (Fig. 5). The facade is comprised of large spandrel panels at each floor level, which sustained no visible damage during the earthquake, and four precast panels enclosing the structural columns at each corner on the front face of the building. Both slab-column joints and column cover panel joints experienced severe cracking; column cover panels were cracked at the location of the plate inserts at panel corners (Fig. 6). The structural drawings were reviewed, and a 3D computer model of the structure prepared. The analytical model includes the main structural components as well as the nonstructural cladding damaged during the earthquake. Frequencies and mode shapes were computed including the effects of soil-foundation flexibility. The focus of the study is to determine the possible role which the heavy precast concrete exterior facade (see details in Fig. 7) played in its response during the 1985 earthquake. The objective of this analysis will be to study the force and interstory drift levels and to explain the damage observed during the earthquake, particularly to the cladding components. Some preliminary findings are now available and will be presented at the upcoming EERI Annual Meeting [14]; final results are expected to be offered at the Final Workshop scheduled for Mexico City on March 16-18, 1989.

Studies of Ductile Rod Connections: This portion of the study represented an extension to the original scope of work on the research project. A report [5] and paper [11] based on this work present the results of this investigation. Finite element models of the ductile rod connection were prepared to support laboratory testing (see Phase II discussion above) and to investigate the effectiveness of the connection in isolating heavy cladding systems from potentially damaging interstory drift. The problem of low cycle fatigue failure of the rods will be further explored in future studies of heavyweight cladding panels supported by ductile rod connections.

Superelement Model for Cladding: A superelement model of a portion of a heavyweight cladding system representative of U.S. practice has been developed for use within an overall building model (see Figure 2 in the Second Progress Report, [2]). The model includes the precast panel, the clip angle attachments, and the supporting spandrel members from the exterior frame. Only the essential freedoms on the periphery are retained for use in the dynamic analysis of the overall structure. Using backsubstitution, the connection and member forces as well as the distortions and stresses in the precast panel can be determined at some specified location on the exterior facade at the completion of the lateral force analysis. This same strategy is currently being employed to model the precast column covers on the Mexican case study building (see Fig. 7b and discussion above).

Finite Element Models of Connection Inserts: Finally, to complement the experimental investigation of the behavior of the different inserts embedded in concrete slabs and subjected to various loading conditions, finite element models were developed for the weld plate and the wedge inserts [7-10]; (see Figs. 1-3 in First Progress Report [1]). These moderate-size models were constructed using a relatively fine mesh in the region of the insert itself, combined with a progressively coarser mesh to model the surrounding concrete, taking advantage of symmetry where appropriate to minimize the modeling effort and the analysis cost.

In the models developed initially, one set of nodes was used for the steel/concrete interface in both the models. But the wedge insert model was later modified so that two coincident sets of nodes were used along the interface, one for the steel elements representing the insert and the other for concrete. Similar modifications are being implemented for the plate insert model also. This facilitates the consideration of varying degrees of coupling between steel and concrete. When the two sets of nodes are connected by a rigid link, complete coupling between steel and concrete is implied. But if not all nodal degrees of freedom of the nodes of one set are rigidly linked to the corresponding nodal degrees of freedom of the other set, only partial coupling is realized. In this case, the steel and concrete along the interface can have different amounts of deformation in those degrees of freedom that are not linked. It is also possible to model flexible links between the two sets of nodes by coupling these sets through springs instead of rigid connections. Although such a representation of the steel/concrete interface by two sets of nodes increases the size and the complexity of the model, it provides a certain amount of flexibility in studying some imperfect bonding conditions that might occur in practice. At present, the MSC/NASTRAN finite element code is being used to study the measured behavior of the U.S. weld plate insert for both linear and nonlinear response levels, and for pull-out, inplane shear and moment loadings applied in the laboratory. A limited amount of additional modeling will be used to understand the measured response of the Mexican weld plate connections which are currently being tested. The insert stiffness and failure capacity values will then be used in the superelement model of the precast column covers for the Mexican case study building (see discussion above).

Implications for Future Research. At present, there is an acute lack of data documenting the good and bad performance of heavy cladding systems on buildings during earthquakes. More field and laboratory test data are needed so that improved analytical models and design procedures can be developed for cladding and its attachments to the primary structure. Experimental and analytical studies of the type described above for the Phase II and III portions of the research program must be continued in order to develop an improved understanding of the behavior of heavy cladding systems on highrise buildings subjected to interstory drift motions.

The authors are confident that rational engineering principles can be applied to the design of heavy cladding systems on buildings. Up to this point, precast cladding design approaches have been concerned largely with isolation of the elements from interaction forces and with insuring environmental and material integrity, especially over time. The result is a state-of-the-art in cladding design in which the cladding assemblies are considered largely as nonstructural architectural components (although our research has shown significant lateral stiffness contributions that may possibly be detrimental to the response during strong motion conditions).

It is also possible that heavy cladding systems will be used in the future for both lateral stiffening and increased damping in buildings [12-14]. To explore this possibility, we now plan to carefully examine the implications of past research results for a radically different approach to precast cladding design. The objective is to develop an integrated design approach that deliberately attempts to involve the precast cladding subsystem in the structural performance of the building. A research project [12] has been proposed that will lead to development of candidate designs and then will test their performance using mathematical models. Detail and component (sub- and super-assemblage) model testing will be carried out in the laboratory to confirm and calibrate the models and design analyses. The motivation for this entire research program is that improper or inadequate design of building cladding can have a detrimental effect on the overall performance of structures during earthquakes.

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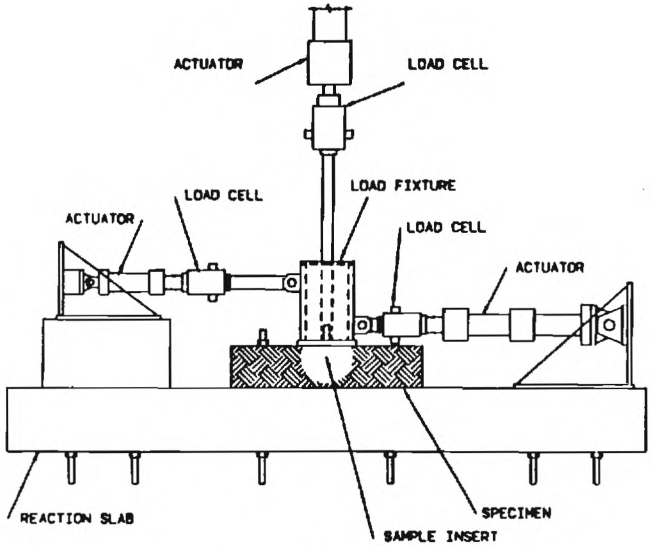


Fig. 1. Connection Test Facility

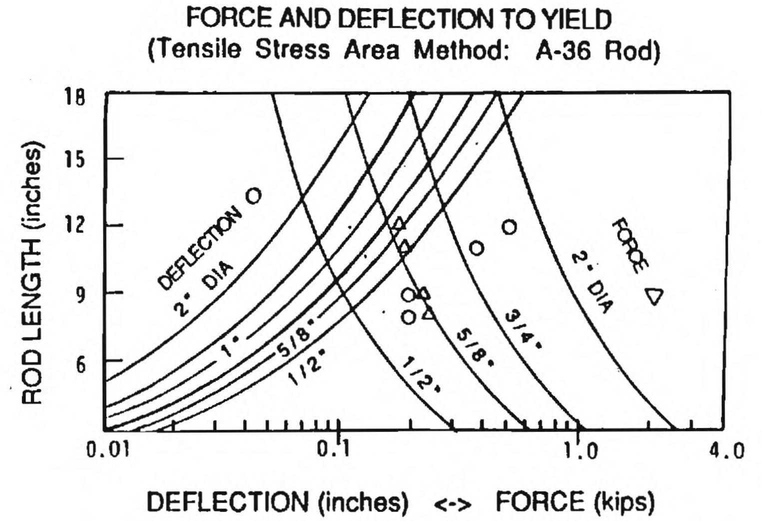


Fig. 3. Push-Pull Comparison with Design Chart

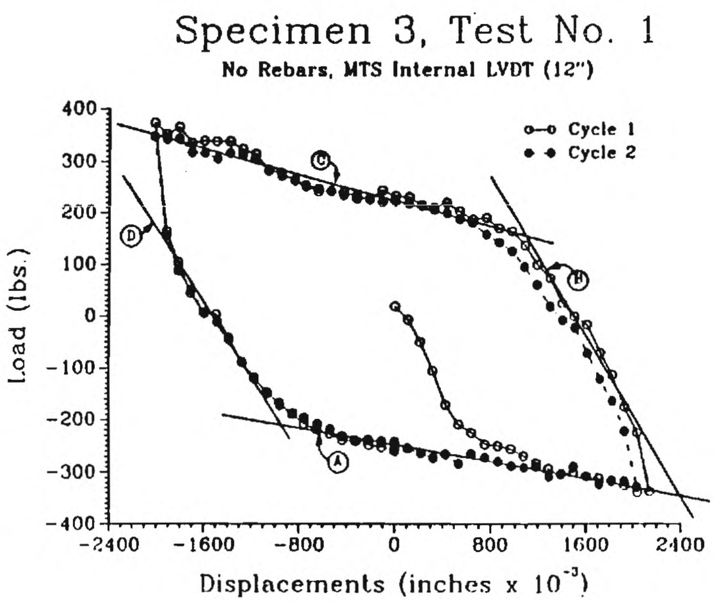


Fig. 2. Typical Push-Pull Connection Behavior

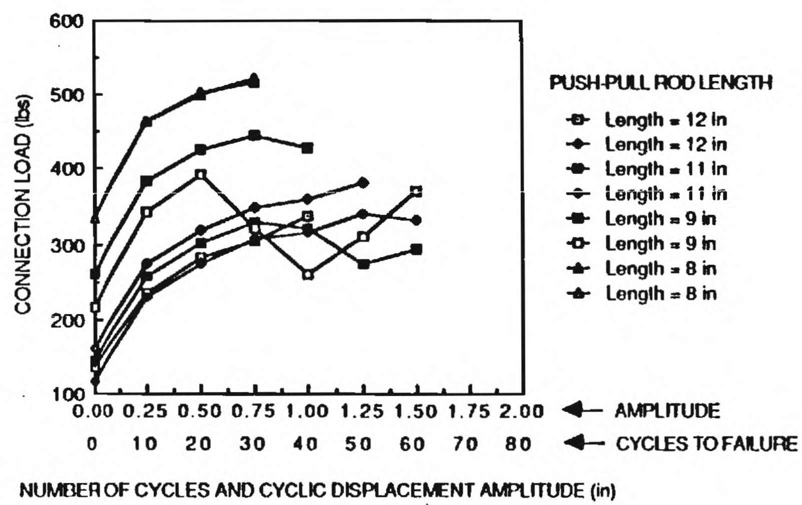


Fig. 4. Push-Pull Cyclic Performance to Failure

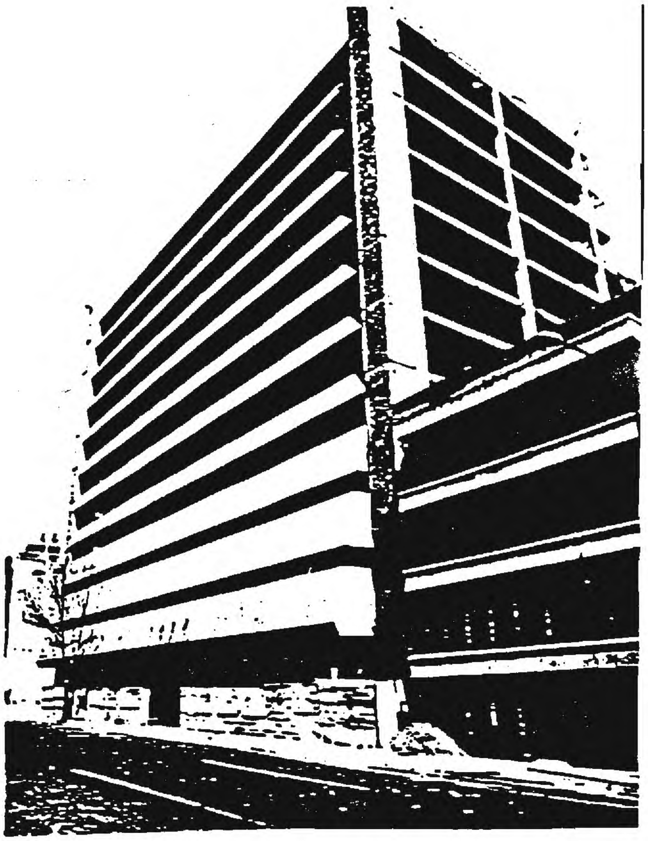
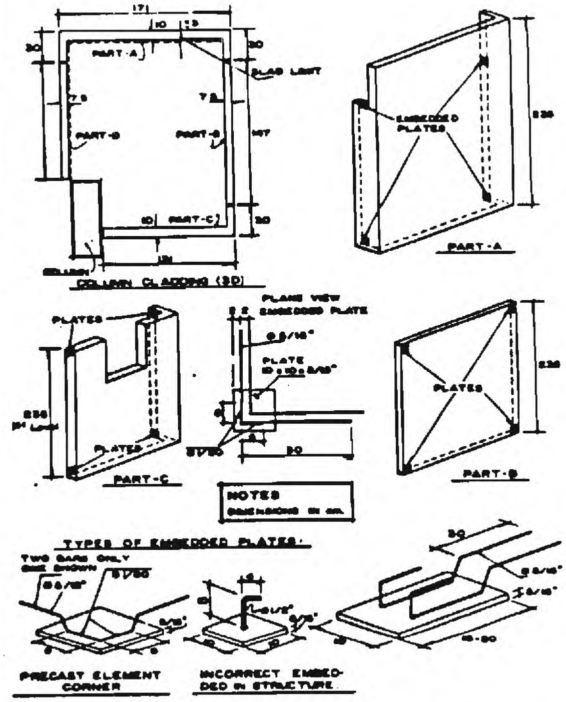


Fig. 5. Mexican Case Study Building



7(a) Column Cover Panels and Weld Plate Embeddments

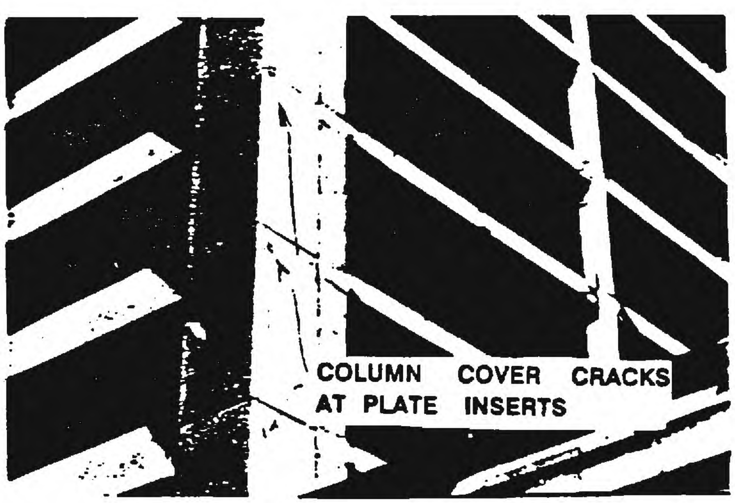
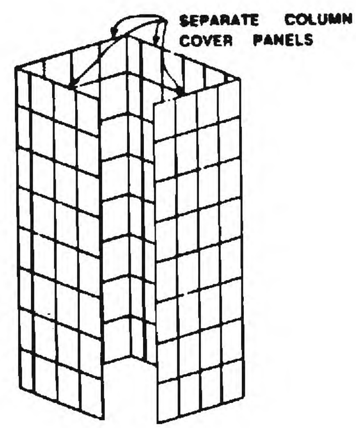


Fig. 6. Cracked Column Cover Panels for Mexican Case Study Building



7(b) Superelement Model of Column Cover Panels

Fig. 7. Column Cover Panels, Connection Details and Superelement Model for Mexican Case Study Building

13.

The Mexico Earthquake of September 19, 1985—Behavior of Heavy Cladding Components

B. Goodno, M.EERI, J. Craig, and A. Zeevaert-Wolff

A combined field study of building cladding performance during the 1985 Mexico earthquake and supporting analytical and experimental studies of cladding systems, typical of those used in Mexico City, are described. Results reported are from an on-going research effort which is broken down into three phases: (I) Nonstructural damage survey and evaluation for selected buildings in Mexico City; (II) Laboratory testing of cladding connections representative of Mexican practice; and (III) Analytical evaluation of a case study building for cladding-structure interaction effects. This study of the behavior of architectural cladding systems in the Mexico Earthquake is complementary to earlier work involving laboratory testing and analytical studies of cladding connection designs typical of U.S. practice. The data gathering, laboratory experimental, and analytical phases were designed to provide a balanced and coordinated attack on the problem of nonstructural performance in earthquakes and to extraction of as much useful information as possible for the benefit of both Mexico and the United States.

INTRODUCTION

The performance of nonstructural building subsystems, such as exterior cladding, is only now beginning to be more fully understood as a result of major research efforts over the past decade [1,3,12,24,33]. In particular, the potential roles of the cladding subsystem in augmenting lateral stiffness under normal loading conditions and in increasing the level of structural damping during earthquake loading are being investigated [10,11,13-16,28-29]. Unfortunately, while analytical methods for evaluating these effects are at a relatively sophisticated level of development [14,19,20,22], it is often not possible to establish reasonable or realistic models for the cladding and the connection constitutive relations due to the acute lack of test and field data [34]. The problem is aggravated by the large variety of cladding and connection configurations that have been developed in practice and the significant regional differences. At the present time, there is a relatively large amount of data concerning the influence of building configuration and structural design on seismic performance, but there has been much less work done in collecting information on the extent and degree of nonstructural damage in past earthquakes. While perhaps seemingly not as important as basic structural issues, the Mexico earthquake - an earthquake that caused unusually high levels of

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damage to the basic structural systems of many buildings [2,8,9,21,31-32] - presented a unique opportunity to study the performance of nonstructural systems under extreme design conditions.

Background

Earlier analytical studies of heavyweight precast cladding elements [11,14] have demonstrated that cladding stiffness contributions to the overall stiffness of the primary structure can measurably affect both the natural frequencies and the linear dynamic response to moderate ground motion. Torsional response is particularly affected, especially if partial cladding failure occurs. Cladding stiffness assessments are highly variable and have been shown to depend quite heavily on the connection performance. Connection slip through use of slotted connections, over-sized holes, etc., lower lateral stiffness dramatically while attachment of panels by welded clip angles result in increased stiffness contributions with the total range being as much as an order of magnitude. Time variation of these properties due to aging introduces additional complexity. A program of experimental testing and analytical modeling is currently underway to provide quantitative information about the performance of a representative set of connection designs [4-7,17,18,23,27,30]. While the initial focus of this work is on the connections, it is anticipated that continuing work will address the properties of the cladding panels themselves and in association with the connections.

Objectives

The primary objective of this study is to develop a functional understanding of the role played by nonstructural cladding elements in the structural performance of buildings under severe ground motion conditions. Specifically, the concern is with both the actual and the potential contributions of cladding to the lateral stiffness under normal loading conditions and the potential energy dissipation (damping) that can be developed under severe loading conditions. Secondary objectives include an assessment of the appropriateness of existing code provisions related to cladding and the identification of potential modifications or extensions that could lead to improved performance.

In the following sections, results of the Phase I damage survey will be described along with a discussion of progress to date on the Phase II experimental studies and the Phase III analytical studies.

PHASE I: DAMAGE SURVEY

In the months following the Mexico Earthquake, relatively little attention was directed to examining or studying the damage experienced by cladding, since the principal concern was clearly to deal with the major structural failures, or where damage was light, to get the buildings back into service as quickly as possible. As a result, our study was initiated with relatively little information or information that was incidental to other surveys and studies. Fortunately, one of the authors (Dr. Zeevaert Wolff) was able to witness the earthquake from the 25th floor of the Torre Latino Americana and to immediately set about photographing and surveying the resulting damage. This information, along with his personal involvement in the subsequent rebuilding phases, has been the principal source of information for this phase of the study.

An initial on-site review in early 1986 of the available information provided the initial direction for the survey and established the evaluation criteria:

(a) Buildings with relatively extensive precast or GFRC cladding systems, and,

(b) Structures in the 10-20 story range, and

(c) Buildings for which both structural design and as-built information was available, or for which on-site inspections could reveal the latter information.

The last requirement ruled out several promising buildings and many buildings that were already stripped of their cladding.

The strategy employed in this phase of the study was to first make a cursory review of as many buildings as practical (25) and then to systematically refine the list, eliminating candidate buildings with the least desirable characteristics, until only three or four qualified buildings remained. The initial list was quickly reduced to 12 structures that met all the basic conditions, and from these, a final list of 4 buildings for which relatively complete architectural and structural drawings were available was assembled. One of these buildings was selected for detailed study, and has been the subject of ongoing research to model both the structure and the cladding as a part of Phases II and III. In addition to the damage surveys, the Phase I study also included a review of the cladding design practice and representative examples of connection designs in the Mexico City region.

The Mexico Earthquake has been well-documented in a number of studies. More than 400 buildings collapsed completely and another 5700 were damaged. The downtown area was the most seriously affected. A combination of soil conditions and ground-structure interactions resulted in unusually severe seismic loadings for buildings between about 15 and 25 stories in height. A number of well-documented reports [2,8-9,21,25-26,31-32,35-36] have presented descriptions of structural and foundation damage. These reports contain large and extensive data bases that are essential for on-going earthquake engineering research. They do not, however, include significant information covering the performance of nonstructural building components in general and cladding systems in particular. Consequently, the present study was initiated with the primary objective of developing a more complete understanding of the performance of building cladding systems that would be complementary to the structural studies. The scope of the present study was restricted principally to relatively heavy cladding systems with potential to contribute significant mass and structural interaction with the main structure. In particular, glass curtainwall systems were not considered because this area was a part of a separate NSF study.

The damage survey was begun in September 1986 one year after the earthquake. Initially, visual observation and personal experience were used to identify buildings. In addition, contacts with contractors, precast fabricators and architects were used to further develop a starting list of several dozen buildings. Due to the lack of cladding information from earlier damage studies, the present survey was necessarily restricted to only those buildings that had not collapsed or were not demolished. One of the most difficult problems was in determining whether any type of engineering information concerning the cladding system design, fabrication and installation was available. In many instances, basic structural information was available but cladding details were missing or incomplete.

Initial Evaluation

A list of 25 buildings was developed based on this first-level evaluation process. The key characteristics of these structures and the cladding systems are presented in Table 1. The buildings were chosen based on the type of facade, the cladding design and the performance during the earthquake and include examples of designs that performed both poorly and acceptably. The sample includes downtown buildings in both the old lake bed region and the transition area with the actual locations identified on the map in Fig. 1. Ground accelerations of as much as 0.2g were reported for the lake area while peak levels in the transition region were estimated to be on the order of 0.05g. The performance of both the building structure and the cladding system are listed separately in Table 1. The evaluation is classified in three levels and is based on a combination of direct observation, discussions with owners and/or architects, and inspection of available engineering drawings, etc. For the cladding, the three levels of performance are:

P: Poor. This indicates that a failure of the cladding and anchorage system was observed ranging from extensive cracking to partial or complete separation of the cladding elements from the structure.

M: Minimal: Only small cracking with no major structural problems; some repair was needed to return to service.

G: Good: No problems were observed or reported.

A similar grading system was used for the structural performance, although at this level of evaluation the actual behavior of the complete building was difficult to estimate from exterior visual inspections and interviews. In this case, the P grading implies collapse or partial failure with heavy cracking in the structure. An M grade indicates damage to such elements as partitions and infill walls, while G indicates very good performance with no repairable damage at all.

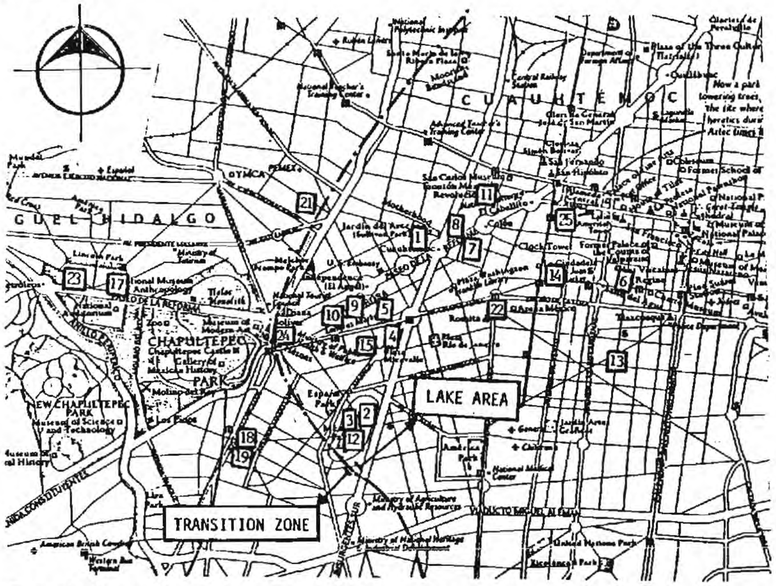


Figure 1 - Survey Building Locations (Buildings 16 and 20 in Transition Zone south of Map)

Table 1 includes information about the design of the cladding systems and references more detailed descriptions in Table 2a. The cladding systems were classified into five groups, A through E, depending on the type of design, the contouring, the construction material and the overall weight. A simple sketch of the vertical plan is included as well to emphasize the overall composition and the relative glass area. Each cladding type is further classified as to the geometry-weight range (1-flat or planar; 2-medium thickness; 3-heavy with extensive three dimensional features). A relatively large number of medium-height buildings in Mexico City employ architectural cladding on only the front (street) face and possibly the side faces. The other faces are typically finished with infill walls which are identified as category E in Table 2a with classifications 4 and 5 denoting the presence or absence of reinforcing.

The information in Table 1 provides the broadest perspective of the damage that was observed approximately one year after the earthquake. The entries are roughly arranged in order of decreasing damage although no specific criteria were used. It is clear that the majority of buildings that experienced some type of damage were in the old lake area which is consistent with the observations of stronger ground motion in this region. It is also apparent that cladding and structural damage was strongly associated with buildings in the 15-20 story height, again consistent with other reports [25-26,35-36].

Detailed Evaluation

The first-level survey included a broad range of heavy cladding systems, that because of the wide variety of design and construction practices and the limited availability of engineering information, were impossible to study in detail within the scope of the present effort. Consequently, the first-level list of 25 buildings was reduced to 12 that could reasonably be subjected to more comprehensive inspection and evaluation. This group is listed in Table 3 which now provides considerable more detailed information about the building configuration and structural design as well as the cladding system design. The classifications used to describe these features are defined in Tables 2b and 2c. Table 2b provides the structural classification under the primary categories of steel frame and reinforced concrete. Table 2c defines the building configuration classification in a consistent manner [1] including vertical, plan and form groupings.

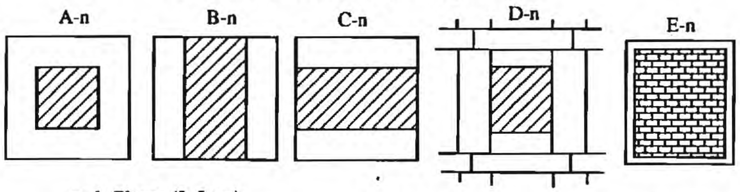
TABLE 1. First-Level List of Survey Buildings

Bldg No.	Cladding Design (Note 1)	Cladding Performance (Note 2)	Structural Performance (Note 2)	Subsoil Conditions (Note 3)	Bldg. Height
1	D1	P	G	L	20
2	A2	G	G	L	6
3	B1-C1	P	P	L	15
4	A3	G	G	L	8
5	B2-C2	M	P	L	11
6	B2	M	P	L	18
7	A1	G	P	L	5
8	B2	G-M	G	L	17
9	B2	G	G	L	8
10	C2	G	G	L	18
11	A2	G	G	L	2
12	C1	P-M	P	L	5
13	E4	P	M-G	L	8
14	D2	P	P	L	12
15	B2-C2	G	M	L	11
16	A3	G	G	T	11
17	B2-C2	G	G	T	10
18	B2-C2	G	G	T	22
19	B2-C2	G	G	T	12
20	B2-C2	G	G	T	16
21	D2	G	G	T	18
22	A2	G	G	L	5
23	D2	G	G	T	22
24	D2	M	P-M	L	8
25	D2	G	P	L	10

Note 1: See Table 2 for nomenclature
Note 2: See text
Note 3: Subsoil area defined as: L-Lake, T-Transition Zone

Each of the twelve buildings was visited and extensive efforts were made to acquire the pertinent engineering information from the owners, architects, contractors and engineers involved. Relatively detailed cladding information was available for eight of the twelve buildings as noted in Table 3. Further study of the data in Table 3 did not reveal any consistent pattern among the various parameters used for the evaluation. The most obvious feature is the general variety of designs, and this is not surprising given the high esthetic and architectural appeal of building cladding systems. The result is a wide variation in visual, material and structural properties that is not easily categorized effectively.

TABLE 2a Cladding Design Configurations



n=1 Planar (2-5 cm)
n=2 Medium thick (5-12 cm)
n=3 Heavy 3D (>12 cm)
Glass
n=4 Unreinforced infill
n=5 Reinforced infill

TABLE 2b Structural Design Classification

A - Steel Frame		B - Reinforced Concrete	
A1 -	Braced	B1 -	Beam & Column
A2 -	Moment Resisting	B2 -	Flat Slab
A3 -	Mixed	B3 -	Waffle Slab
		B4 -	Shear Walls
		B5 -	Prestressed

TABLE 2c Building Configuration [1]

A: Vertical		B: Plan		C: Form	
A-1	Discontinuous Shear Wall	B-1	Symmetric	C-1	Regular
A-2	Soft Story	B-2	L Shape	C-1	Setback
A-3	Large Variation in Column Stiffness	B-3	U Shape		
A-4	Small Variation in Column Stiffness	B-4	T Shape		
		B-5	+ Shape		
		B-6	Irregular Plan (complex)		
		B-7	Variation in Perimeter Stiffness		
		B-8	Asymmetrical Core		

Examples of Cladding Damage

In view of the high variability in the information developed from the second-level study, it is perhaps more effective to describe and illustrate some of the cladding performance details for selected buildings. Discussions for ten buildings, including three not on the second-level list, are presented below. Building locations are shown in Fig. 1.

Building 1: Figure 2 shows the before and after-the-earthquake views of this structure which employed a core and tube structural system and a natural stone facade attached with steel wire to the supporting structure. The building was designed in accordance with the 1976 code, and the primary structure performed well. The stone panels were cracked in many places following the earthquake and several panels fell from the structure. Due to its high commercial visibility and relatively light damage, the structure was quickly repaired and the facade replaced entirely with a glass curtainwall supported by a light steel framework attached to the building structure.

TABLE 3 Second-Level Survey Buildings

Building No.	Building Config. (Table 2c)	Cladding Design (Table 2a)	Structure Design (Table 2b)	Details Available	Cladding Perform.	Structure Perform.	Further Study
1	A4-B1-C1	D1	B1	Yes	Failed & changed	G	Yes
2	A2-B1-C1	A2	A3	No	Good	G	
3	A2-B3-C1	B1-C1	B3	Yes	Panel delamination	P	Yes
4	A2-B1-C1	A3	B1	No	Good	G	
5	A4-B8-C1	A2-C2	B3	Yes	Structure failed; local connection failures	P	Yes
7	A4-B6-C2	A1	B1	Yes	Structure failed but cladding reused	P	
8	A4-B1-C1	B2	B1	No	Few joint problems	G	
9	A4-B6-C2	B2	B3	Yes	Minor problems	G	
10	A2-B1-C2	C2	B3	Yes	Good	G	
16	A2-B7-C1	A3	B1	Yes	Very good	G	Yes
17	A2-B1-C1	B2-C2	B1	No	Minor problems	G	
20	A2-B7-C2	B2-C2	B3	Yes	Good	G	

Figure 2 - Building 1 Before and After Recladding

Building 2: The building shown in Fig. 3 had a soft first story composed of steel columns which support the concrete frame structure above and enclose the first story parking area. The heavy precast cladding panels which made up the facade appeared to be very similar to those used in the U.S. Both the structure and facade appeared to experience no visible signs of distress in the earthquake. Nevertheless, the owners were unwilling to provide either information on or access to the building for our studies.

Building 3: This 15 story concrete frame structure with waffle slabs (Fig. 4) was unsymmetric in plan and experienced heavy damage to the framing and masonry infill walls. The cladding system was composed of heavy precast panels which were attached to the masonry infill by mortar reinforced with 1/8 inch steel wire tied to 4 inch nails driven into the brick masonry (see Fig. 15). The cladding panels delaminated from the mortar backing (Fig. 5) and were in danger of falling from the structure. The structure was closed following the earthquake pending a decision to repair or demolish.

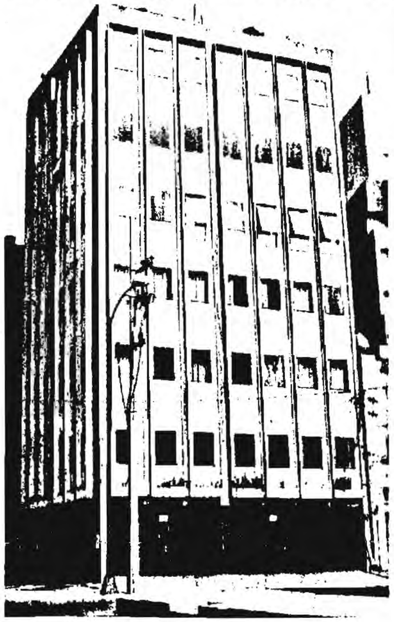


Figure 3 - Building 2

Figure 4 - Building 3

Building 5: The 11 story concrete frame structure with waffle slabs shown in Fig. 6 had extensive structural damage, primarily at the joints. The precast column cover panels were attached to plates embedded in the floor slabs (see Figs. 16,17) and experienced extensive racking at the corners at the location of the plate inserts in the panels (see Figs. 7a,b,c). The spandrel facade panels along the inclined front face of the structure were not damaged. This structure was chosen from those in the Phase I survey for detailed analytical evaluation in Phase III (see discussion below). The weld plate inserts in the panels are similar in concept to those used in U.S. construction and will be subjected to pull out, shear and moment loadings in the laboratory in the Phase II program (see below).

Building 7: The reinforced concrete frame structure shown in Fig. 8 sustained some structural damage, and was being repaired when the photo was taken, but the lightweight fiberglass cladding panels were not damaged. The panels were attached to the floor slabs with a flexible tee connector bolted into the floor slab which effectively isolated the panels from interstory motions. The cladding was removed from the structure and sold for use on another building which was also under repair.

Building 8: The cladding system for this 17 story structure sustained localized damage due to pounding from an adjacent lower structure which was later demolished.

Building 12: This apartment building experienced large relative interstory motions which caused almost total glass breakage and buckling of the window frames. However, the bands of spandrel cladding panels were undamaged.

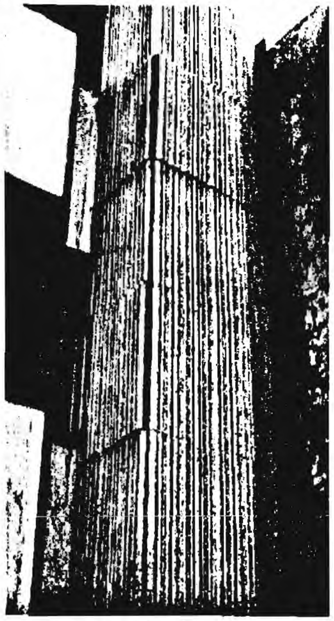


Figure 5 - Building 3 Panel Delamination

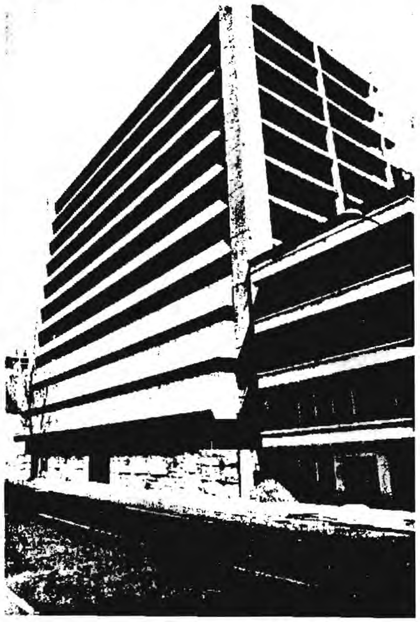


Figure 6 - Building 5

Building 13: The structure in Fig. 9 was in good condition following the earthquake, but the masonry facade failed due to insufficient anchorage at the base and had to be completely replaced. This type of masonry infill facade is quite common in Mexico, particularly for the side and rear faces of the building; architectural panels are generally reserved for the front of the building. The building was designed using the 1962 code.

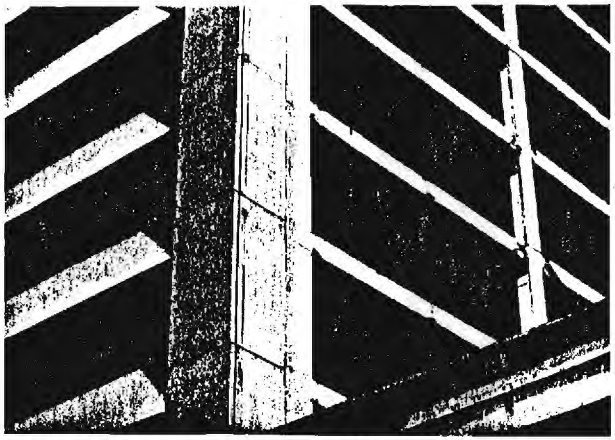


Fig. 7a. Building 5 Cladding and Column-Slab Failures

Building 16: The heavy precast cladding system for this structure (Fig. 10), located in the transition zone, is very similar to that used in the U.S. Both the structure and cladding performed very well during the earthquake.

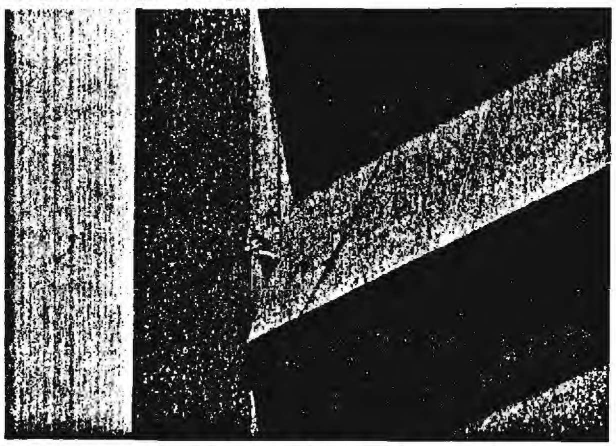


Figure 7b - Close-up of Building 5 Column Cover Cladding Failure

Building 25: This older 10 story structure was built in the 40's and has a natural stone facade. The building was designed for a lateral force of 2.5% of gravity but no interstory drift requirements were used in the design of the cladding. The structure was damaged in the 1985 earthquake and later repaired. The cladding performance was adequate considering its age and

the fact that it has been subjected to a number of earthquakes in its 40 year history. There was no information on the state of the cladding prior to the 1985 earthquake. Several panels were dislodged from the structure at the third floor level.

General Observations

The anchorage of heavy cladding elements in Mexican cladding construction practice is commonly achieved by inserting steel plates in the concrete structure and placing corresponding inserts in the cladding elements. A variety of different means, including simple clip angles but also involving *ad hoc* fixtures, is used to make the connection between the cladding and the structure. Typical generic details as excerpted from engineering drawings for the second-level list of 12 buildings are presented in Fig's 11-17. Figure 11 shows a typical detail of the anchorage to a steel frame structure while Fig. 12 shows the anchorage of relatively light precast cladding to a reinforced concrete structure. The joint is finished by welding both parts together with a triangular steel plate or a clip angle. The details of the attachment of a very long precast element (more than 4 m) is shown in Fig. 13. Details of the anchorage for an inclined facade are shown in Fig. 14.

Figure 7c - Building 5 Cladding Failure

Figure 8 - Building 7 (Cladding for Sale)

A key feature of all the designs examined is the almost complete lack of any provision for relative movement between the cladding panels and the supporting structure. None of the buildings in the 10-25 story height range surveyed in this study were observed to incorporate any type of isolating connections for this purpose. This is in contrast to the common practice in seismic regions of the US where a variety of methods have been developed for handling relative movement. For example, the popular "push-pull" or ductile rod system widely employed in West Coast practice was not found in any of the buildings examined. It should be pointed out, however, that the study did not include taller buildings (none of which suffered noticeable damage) nor other commercial buildings that did not suffer damage (in these cases owners were reluctant to share design information).

In at least two cases of severely damaged facades, the cladding elements were attached to the structure by steel wire inserted in the structure and the cladding elements. This type of practice appears relatively common in many lower cost buildings up to 20 stories. Details of these anchorage systems were not provided in the available structural drawings, and only verbal reports from the resident building supervisor were obtained. In one of the buildings, a direct physical examination, including partial removal of several panels, revealed the details shown in Fig. 15. In this case the thin precast cladding panels were attached to the building using mortar "reinforced" with 1/8" (3.2mm) steel wire looped around nails driven into infill walls constructed of common bricks. This type of attachment performed very poorly since it was unable to isolate the thin cladding panels from the structure.

Figure 9 - Building 13 (Cladding failed but structure survived)

In typical Mexican practice heavy cladding designs are proposed by the architect to satisfy architectural and esthetic requirements. A precast supplier is contracted to produce the system and a structural engineer is generally retained to design the anchorage system that will be employed. In some cases the precast contractor proposed the connection designs. When the anchorage system is proposed by the structural engineer, the responsibility for attachment of the cladding is taken by the structural engineer. Otherwise, it is the responsibility of the fabricator. It appears, however, than for lighter and less expensive cladding, the design responsibility may often be handled by the architect or the precast supplier alone, and the installation left largely to the skill and resourcefulness of the building contractor. In several instances, it was clear that the cladding erector simply used "available materials" and fashioned connections out of scrap reinforcing bar and the like.

Some evidence was found that repair of cladding systems, although a relatively small part of the total rebuilding effort, is occasionally being handled in a haphazard manner. In cases where the previous cladding system had been removed (perhaps for structural repair and strengthening), the new panels were attached using improvised connections that in at least one case involved direct welding of the connections to exposed reinforcing bars in the main structure. In this case the connections themselves were simply short pieces of reinforcing bar.

There are no specific provisions in the Mexico City seismic codes (1957-1968) for the design of heavy cladding elements. General requirements for maximum drift, glass breakage, pounding by adjacent structures and design accelerations indirectly affect the design of cladding systems. Related requirements govern the design of fixtures attached to the structure.

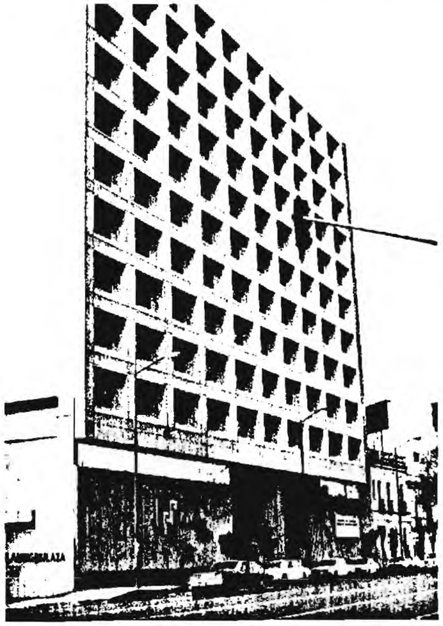


Figure 10 -Building 16 Showing No Damage

Study Building

The second-level list of 12 buildings was reduced to 4 buildings for more detailed study, including discussions with architects and engineers where possible. From these four buildings (see Table 3), Building 5 was selected as the study building on the basis that it most closely met the three criteria noted earlier. Building 5 (Fig. 6) is located in the old lake bed region, and its waffle slab reinforced concrete structure suffered cracking at the slab-column connections. The heavy cladding system appeared largely unaffected, but closer examination revealed a number of instances of connection failure, in some cases with visible results (Fig.

7). The most dramatic problem involved the failure of supporting column for a water tank on the top floor. The resulting tank failure caused a partial collapse of the rear of the building.

Details of the cladding design are shown in Figs. 16-17. The design consists of column covers at each front corner as shown in Fig. 17 with sloped spandrel (longitudinal) elements between the columns (Figs. 6 and 17). The connection anchors were fabricated from steel plate with welded reinforcing bars arranged to conform to the panel geometry. The weld plates were attached directly to embedded inserts in the structure using simple clip angles, rectangular bar stock, or direct welding. Failure of the connections, particularly the cladding inserts, occurred most consistently in the column covers on parts A, B and D as shown in Fig. 16. There was some indication in the discussions that the embedded plates were not fabricated as specified with the full 30 cm lengths of reinforcing bar, although it was not possible to verify this directly. The spandrel panels (Fig. 17) were attached directly to the top of the slab near the front edge and did not appear to have suffered any damage.

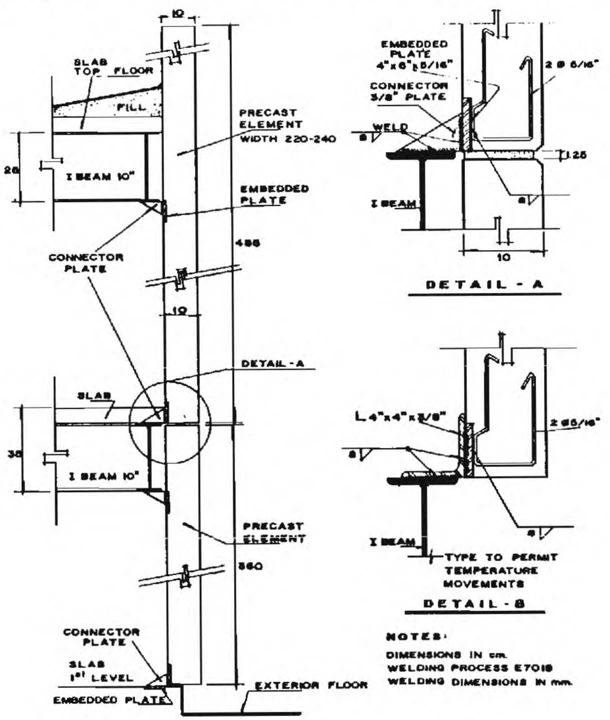


Figure 11 - Typical Heavy Precast Cladding Design

Complete engineering drawings for the building and the cladding system were obtained and, together with information from the architect, have formed the basis for the Phase II and Phase III studies outlined below.

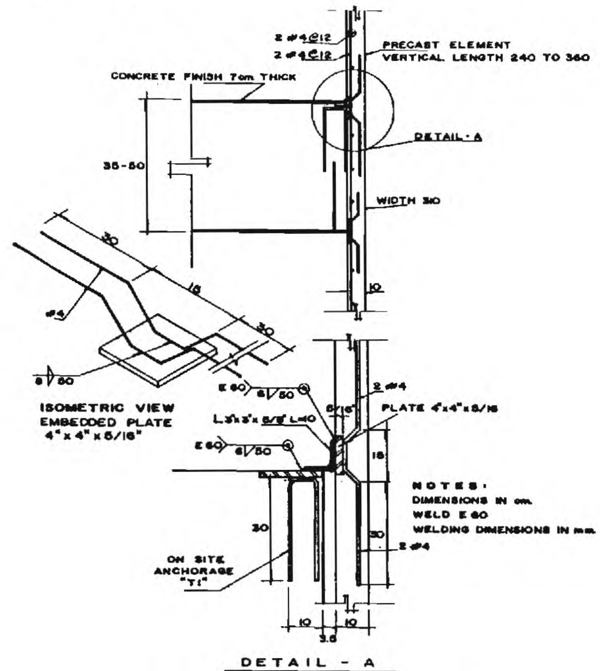


Figure 12 - Typical Light Precast Cladding System

Phase I Conclusions

During the Mexico Earthquake, the overall behavior of heavy precast cladding systems in the study buildings was not good. The study did not attempt to exhaustively survey all classes of buildings, but tended to concentrate on the more vulnerable structures for which engineering information was accessible. Nonetheless, the survey included examples of both good and poor behavior. Generally, it was found that relatively inflexible connections performed poorer, especially in the old lake region where building motions were most severe. Buildings 1, 3, 13 and 14 are examples of this kind of design, and the cladding performed very poorly with replacement as the only practical repair option. In some cases (Buildings 5 and 7) the building structure required extensive repair, and yet the cladding sustained only relatively minor damage. The flexible connections in Building 7 performed quite well and the cladding survived without damage. Buildings 2, 4 and 16, on the other hand are examples where the cladding system worked well. It should be noted, however, that while many such cladding systems did not show outward evidence of damage, it is possible that hidden damage due to inelastic deformation exists, given the comparatively rigid attachment systems that appear to be favored by designers.

This study should not be interpreted as a comprehensive survey of cladding damage, but rather it should be considered as a limited review of available information on cladding system performance. The study was limited by two primary factors. First, it was initiated one year after the earthquake when much of the relevant cladding information, particularly about totally collapsed structures, was lost. Second, it was limited by the availability of engineering information about the design and installation of cladding systems that survived without damage or were subsequently repaired. It is fortunate that several owners, architects and engineers were willing to share this information. Finally, the principal purpose for the study was to identify an appropriate building that would become the focus for a much more detailed examination of cladding-structure performance in Phases II and III.

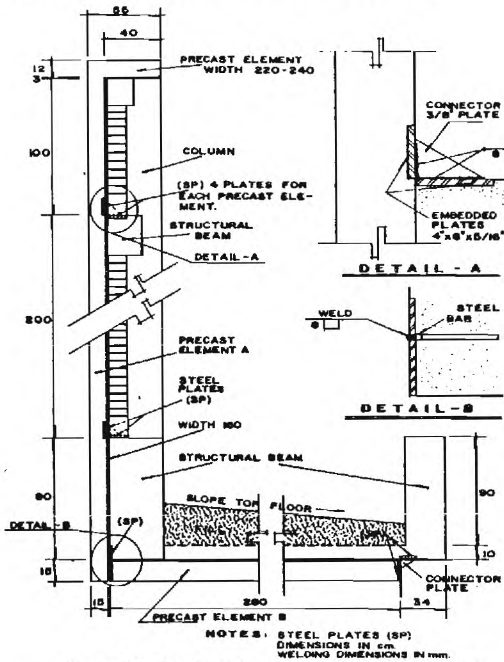


Figure 13 - Detail of Very Long (4 m) Precast Panel

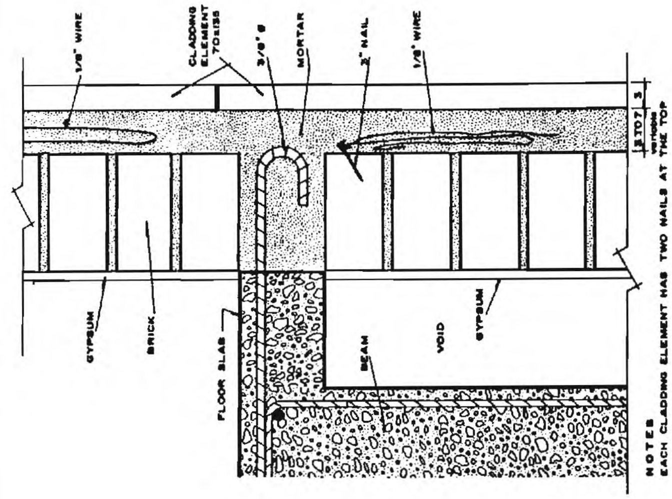


Fig. 15. Detail of Cladding Panel Attached to Infill Wall Using Reinforced Mortar

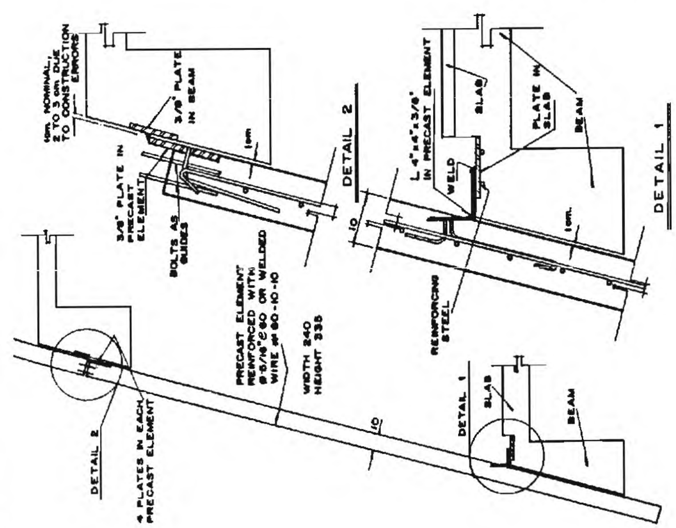


Fig. 14. Details of an Inclined Cladding Panel

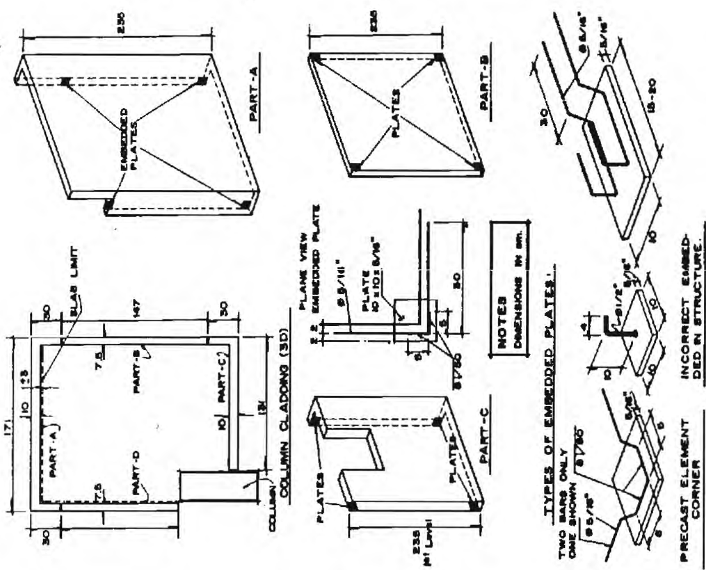


Fig. 16. Details of Column Cladding Panels for Study Building

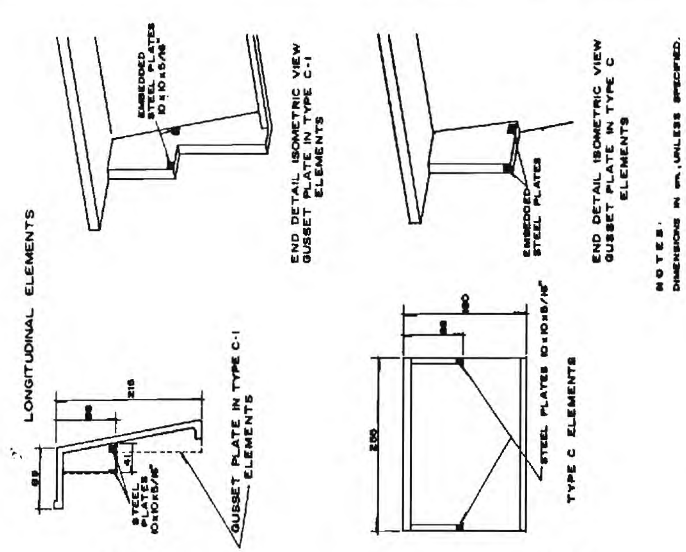


Fig. 17. Details of Spandrel Cladding Panels for Study Building

PHASE II: LABORATORY TESTING

The Phase I study identified several types of cladding connections that appear to be widely used in practice. Of these, the weld-plate and its variations are the most common for relatively heavy cladding, but direct attachment via reinforced grouting is often employed for lightweight cladding. Push-pull or ductile rod isolating connections common to West Coast US practice do not appear in common use, and no examples of bolted inserts were observed. As a result, the Phase II tests were designed to explore the performance of:

- Welded connections using embedded weld plates that are typical of those actually employed on the building selected for detailed modeling,
- Several types of reinforced grout connections.

Consideration was initially given to testing several types of reinforced grout connections, but difficulties in designing the experimental program coupled with similar difficulties in developing suitable analytical models led to elimination of this class in favor of the push-pull or ductile rod connections which are more widely employed in US practice.

A special testing facility and data acquisition system was developed to carry out the testing. The facility is designed to handle a variety of inserts that are cast into a test slab measuring 3 ft. (91 cm) square by up to 8 in. (20 cm) thick. The slab is fixed to a reinforced test bed using up to 8 tie rods and grouting. The various load conditions can be applied by means of conventional multi-axis servo-controlled hydraulic actuators. The present fixture was designed to allow the following combinations of loading:

- Direct pullout (normal to slab),
- Single axis inplane shear load (parallel to slab which simulated gravity or inplane lateral or racking loads),
- Single axis bending (about an axis parallel to slab which simulates bending loads),
- Combinations of (b) and (c).

The fixture was modified to allow testing of ductile rod connection elements arranged in a push-pull connection design. Typical details of the fixture are given in Figure 18. The current arrangement does not allow application of torsion loads (moment loads about an axis normal to the slab) which would simulate the loading due to inplane racking motion of the building face.

The data acquisition system consists of an IBM PC/XT with associated hardware and software that can be used to monitor and control each test. Monitoring functions are handled by multi-channel strain and voltage measuring instruments , and control is accomplished either manually or with a custom-built D/A converter subsystem. All programming for testing and analysis is handled in Turbo Pascal or with spreadsheet software.

Testing of the push-pull ductile rod connections has been completed [6,23] and tests of the weld-plate inserts are currently underway. This type of connection design is widely employed in West Coast US practice as a means for providing cladding-structure isolation for inplane motion while at the same time providing adequate out-of-plane resistance to seismic and environmental loads. These connections are typically used for two of the panel connections and rigid inplane connections are used at the remaining two locations. Under strong motion, the connections allow large inplane movement between the cladding and the supporting building structure.

Standard 0.625 in. (1.59 cm) diameter Dayton F-42 loop ferrule inserts, both with and without reinforcement, were embedded in 5000 psi (725.7 kN/m2) reinforced concrete test panels. The connections were fabricated from different lengths of A-36 threaded steel rods and were tested under transverse (shear) loading. Several of the connections were also tested under cyclic transverse loading until fatigue failure occurred.

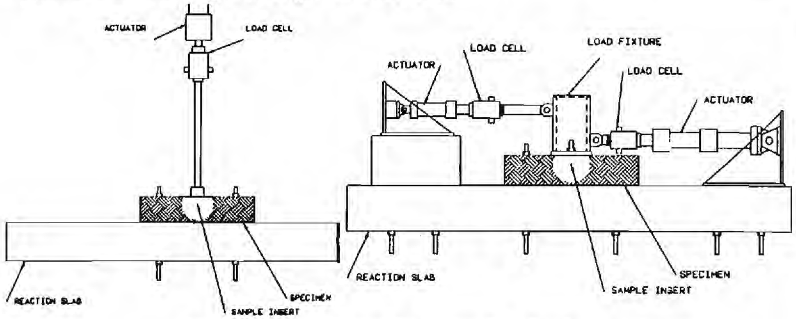


Figure 18a - Test Fixture for Precast Cladding Inserts

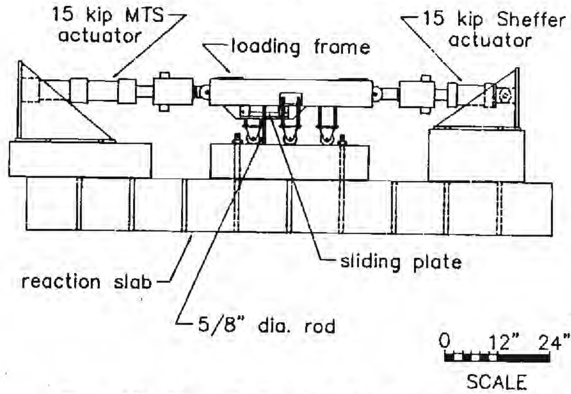


Figure 18b - Fixture for Push-Pull (Ductile Rod) Tests

The experimental tests, along with the analytical models developed under Phase II (below), have confirmed the basic behavior assumed for these designs. Measured stresses and deflections agreed well with simple linear elastic beam models for the ductile rods. The beam models were also able to accurately predict the onset of inelastic behavior at large levels of transverse displacement. However, the most significant result of these tests was the observation of low-cycle fatigue failure of the ductile rod. Various lengths of ductile rod connections typical of common practice were subjected to systematically increasing cycles of transverse (lateral) displacements with no axial load applied. In all cases tested (8 total), each of the rods experienced low-cycle fatigue cracking at one or both roots (panel end and building end) for displacement amplitudes up to but not exceeding typical (UBC) code provisions for interstory drift. In addition, in one half of the cases complete fracture occurred at one or the other end within 25 displacement cycles.

Taken together, these observations confirm the accuracy of both the elastic and inelastic static connection design models, but they strongly indicate that a static analysis is inadequate for predicting the behavior during strong motion conditions. While it seems unlikely that virgin connections will fracture under a single earthquake, it appears likely that some connections will fail after exposure to several moderate or strong earthquakes. As noted below, simple connection failure models based on these experimental results are being incorporated into analytical building models which will be subjected to different earthquake records.

The weld-plate connection test program is currently in progress. Connection specimens and test fixtures have been designed and the preliminary tests are underway. Connection specimens representing all major types of cladding connections employed on the Phase I study building are being investigated. Particular interest is being given to connections typical of those used at external vertical corners and at thin edges and corners of individual panels.

PHASE III: ANALYTICAL STUDIES

The major activities in the analytical program have been concentrated in four principal areas: (1) preparation of the computer model of the Mexican case study building; (2) extension of the analytical and experimental studies of wedge insert and embedded plate connections to include ductile rod systems; (3) continued development of the superelement model of one cladding panel and its supporting connections and framework; and (4) assemblage of detailed finite element models for the cladding connection inserts to support the laboratory experimental program (Phase II). Each of these topic areas is discussed separately below.

Mexican Case Study Building

Building 5 described above was selected as the case study building. The structural drawings have been reviewed, and a preliminary 3D computer model of the structure has been prepared (Fig. 19). The building is being studied to determine the possible role which the heavy precast concrete exterior facade played in its response during the 1985 earthquake. The analytical model includes the main structural components as well as the nonstructural cladding which experienced some damage during the earthquake. The soil-foundation system will be modelled initially using linear springs. Both response spectrum and time history dynamic analyses will be performed. The objective is to study the force levels experienced by both structural and nonstructural components and to explain the damage sustained during the earthquake, particularly to the cladding components. The more refined models of the cladding developed in past studies [14,20] will be altered as needed and integrated into the overall model of the concrete frame structure as the study progresses.

Studies of Ductile Rod Connections

A report [23] based on this work presents the results of the investigation of the mechanical performance of push-pull (ductile rod) connections. (Connections of this type are reportedly [9] used for precast cladding in Mexico, but the authors did not encounter any in the Phase I survey.) The tests were carried out on specially designed laboratory specimens using a fixture that was capable of applying transverse (shear) and normal (pull-out) loads to the connection (see discussion under Phase II above). Strain gages were placed at various locations on the insert, the ductile rod and the reinforcing material. Displacement and strain data were taken and evaluated in order to determine the stiffnesses and load histories for both the connection and the insert.

A spring-supported simple numerical beam model with 24 beam elements was used to model the ductile rod connection. Parameters of the model were estimated using strain and displacement measurements for typical ductile rod lengths. The effectiveness of the connection model was studied using an existing numerical linear frame-panel model of a portion of a typical steel frame building. It was shown that the push-pull model was effective in isolating the cladding panel from the underlying building structure. However, the experimental results suggested that low cycle fatigue failure of the ductile rod under large-motion conditions was highly likely for the rod length typically employed in practice. The possibility of fatigue failure will be explored in future studies of the overall building model with heavyweight cladding panels supported by ductile rod connections.

Superelement Model for Cladding

A superelement model for a representative portion of a heavyweight cladding system was developed for use in the overall building model (see Fig. 20). The model included the precast panel, the clip angle attachments, and the supporting spandrel members from the exterior frame [20]. By condensing out the extraneous interior degrees of freedom from the model, only the essential freedoms on the periphery were retained for use in the dynamic analysis of the overall structure. In subsequent studies, the connection and member forces as well as the distortions and stresses in the precast panel will be determined at some specified location on the exterior facade at the completion of the lateral force analysis. This model is expected to be used in the analysis of the Mexican case study building.

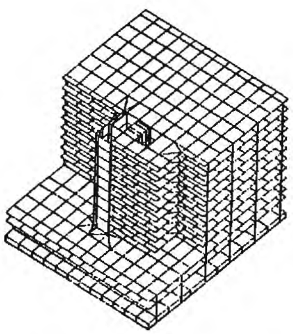


Figure 19 - Building 5 Computer Model

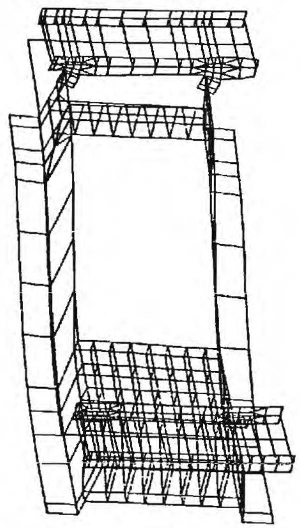


Figure 20 - Cladding Panel FEM Model

Finite Element Models of Connection Inserts

Finally, to complement the experimental investigation of the behavior of the different inserts embedded in concrete slabs and subjected to various loading conditions, finite element models were developed for the weld-plate and the wedge inserts [25]. These moderate-size models were constructed using a relatively fine mesh in the region of the insert itself, combined with a progressively coarser mesh to model the surrounding concrete, taking advantage of symmetry where appropriate to minimize the modeling effort and the analysis cost (see Figs. 22 and 23 for wedge insert connection).

The wedge insert (Fig. 21) was modeled with 106 four-noded quadrilateral and 23 three-noded triangular shell (plate) elements, and 10 eight-noded hexahedron and 2 six-noded pentahedron solid elements. The shell elements were assumed to possess both in-plane and bending stiffnesses. Modeling of the concrete slab was accomplished using solid elements consisting of 199 hexahedron, 600 pentahedron, and 605 four-noded tetrahedron elements. The complete model is shown in Fig. 22.

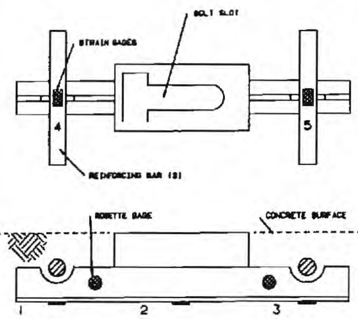


Figure 21 - Wedge Insert

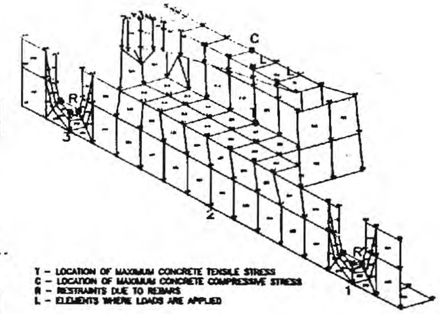


Figure 22a - FEM Model of Insert

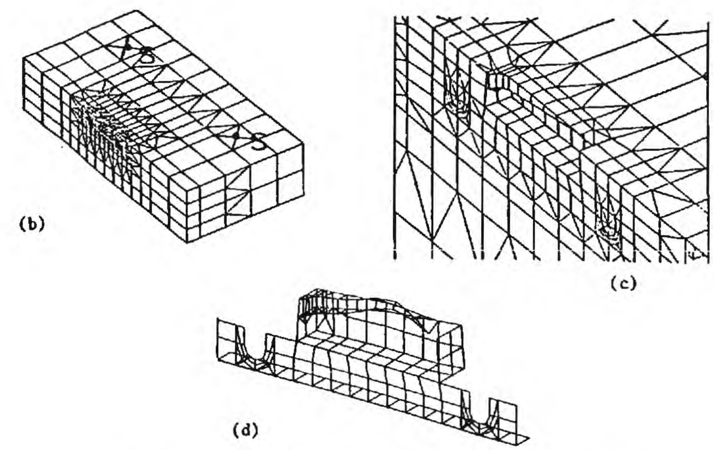


Figure 22b-d - FEM Insert Model in Concrete and in Deformed Shape

In the model developed initially, perfect bonding was assumed between insert and concrete on all contact faces, with one set of nodes being used for the steel/concrete interface. But in order to introduce some flexibility into the model so that other types of bonding conditions can be accommodated, modifications were made to represent the interface by two coincident sets of nodes, one for the insert elements and the other for concrete. This facilitates the consideration of varying degrees of coupling between steel and concrete. When the two sets of nodes are connected by a rigid link, complete coupling between steel and concrete is implied. But if not all nodal degrees of freedom of the nodes of one set are rigidly linked to the corresponding nodal degrees of freedom of the other set, only partial coupling is realized. In this case, the steel and concrete along the interface can have different amounts of deformation in those degrees of freedom that are not linked. It is also possible to model flexible links between the two sets of nodes by coupling these sets through springs instead of rigid connections. Such a representation of bonding, however, is somewhat less sophisticated than some bond-slip models currently available but it does provide, in the present context, some opportunities to study non-ideal bonding conditions that may occur in practice. The result of the separation of the interface nodes was to increase the total number of nodes from 879 used in the original model to 1043 in the modified model.

Experimental data available to date for the wedge insert from pullout tests conducted on several specimens have been compared to the finite element model predictions [27]. These efforts are continuing. Any correlation between analysis and experiment is complicated by the fact that different types of behavior were observed in different insert specimens during the pullout tests. For one of the specimens that showed nearly linear behavior over the loading range employed in the tests, excellent agreement was found between the test data and linear finite element analysis with complete interface coupling, at least for those locations where strains were measured. But the other specimens were found to exhibit significant nonlinear behavior in the form of a change in slope of the load-strain curve for load values above a certain level. In fact, for one of the specimens, changes in both the magnitude and the sign of the slope were observed at one of the measurement locations. If experimental errors are discounted, such behavior points up the differences between various specimens themselves, which in turn is an indication of the high variability or nonuniformity that may be expected in crucial aspects such as bonding.

The observed nonlinearities may be caused by, among other things, nonlinear material behavior of concrete due to factors such as exceeding the usually small tensile strength at various locations around the insert. But another cause that is more likely involves the debonding of steel from concrete at different interface regions. The linear finite element model was modified in an effort to understand and investigate the nonlinear response. In the first attempt, gaps were assumed to exist between steel and concrete along one or more contact faces. As loads are applied, such gaps may open or close depending on the local deformations. In the case of gap opening, no load is transmitted from the insert to concrete. On the other hand, if the displacements are such that the gaps tend to close, loads are transmitted in the axial and transverse directions. Coefficients of friction were specified for use in determining the amount of load that can be transmitted in the transverse direction. For load values beyond this amount, sliding was assumed to occur. The MSC/NASTRAN finite element code was used to model such effects.

By introducing gaps along one or more faces, the possibility of reproducing some of the nonlinear experimental data has been explored. These efforts have been partially successful to date, showing that the appropriate boundary conditions for several of the specimens lie somewhere between the unbonded and fully bonded states over at least a portion of their full range of behavior. In future studies, finite element models of this kind will be prepared for the weld plate connection insert commonly used for heavy cladding in Mexico City.

CONCLUSIONS

The principal conclusions of this study to date are as follows:

1. As with most major earthquakes, the initial responses were to deal with search and rescue, lifeline systems damage, and major structural failures. As a result, there was little chance (to the authors' knowledge) to gather data on damage to cladding, architectural components and contents in the 1985 Mexico Earthquake. As a result, perishable but potentially valuable data was lost while cosmetic repairs were quickly made or buildings were demolished. After several months, owners became more reluctant to discuss the details of the damage sustained to their buildings because of potential liability issues. It also became much more difficult to gain entrance to buildings to attempt to reconstruct damage information on the basis of observed repairs. This situation has occurred in many past earthquakes and is not unique to Mexico.

2. From the survey of 25 buildings with heavy cladding systems in Mexico City, the following preliminary summary statements can be made concerning cladding and structure performance:

   a. 10 of 18 buildings in the lake bed were rated as having good cladding performance, 3 of 18 showed fair performance, and 5 of 18 showed poor cladding performance.

   b. All 7 of the buildings in the transition zone had good cladding performance.

   While it is not possible to draw statistically meaningful conclusions from this information, the results do suggest that design practices for heavy cladding systems may not be adequate for expected earthquake loadings. Clearly, the vast majority of buildings in Mexico City survived with little or no damage. Of the damaged buildings, those that suffered major structural failures, not surprisingly, almost always experienced cladding damage as well. On the other hand, several study buildings were found to have minor or no structural damage, and yet experienced significant cladding damage.

3. Past studies have shown that heavy cladding systems and interior partitions can stiffen buildings and alter their response during the initial stages of the earthquake compared to the bare frame model used for design of the structure. Localized failure of cladding and other nonstructural components can contribute to increased torsion of the overall structure. One of the 25 buildings investigated in the survey of heavily clad buildings was selected for in depth study by the project participants; the cladding was damaged during the earthquake at its attachment points to the structure and the primary structure was also severely damaged. Present cladding models are being used to investigate the role which cladding may have played in the overall response of this structure.

4. During the course of the building survey referred to above, we observed several instances in which the repair and reconstruction of cladding systems were, in our opinion, not based on rigorous analysis and design procedures which are required for repair and rehabilitation of the primary structure. As a result, the cladding components may not be properly attached to the structure. In these cases the repairs to architectural components may not have received as careful a review and field inspection as those for the structural framing. Again, this situation is not unique to Mexico and is not unexpected given similar experiences in past earthquakes where there is pressure to repair structures as quickly as possible but where standards to guide the repair of nonstructural elements in buildings are lacking. This is significant because there were a number of instances in which the entire cladding system was removed from the structure, typically to provide access for structural repairs, and subsequently was replaced.

5. While a major effort was devoted to repair of the primary structure (and this is certainly proper), a corresponding level of attention was not directed to the design and

reattachment of the new or repaired cladding systems. At the same time, it must be recognized that there is not much information and/or experience to guide the designer and contractor in carrying out this kind of work.

6. At present, there is an acute lack of data documenting the good and bad performance of heavy cladding systems on buildings during earthquakes. Both field and laboratory test data are needed so that improved analytical models and design procedures can be developed for cladding and its attachments to the primary structure. Experimental and analytical studies of the type described above for the Phase II and III portions of the research program must be continued in order to develop an improved understanding of the behavior of heavy cladding systems on highrise buildings subjected to interstory drift motions.

7. The authors are confident that rational engineering principles can be applied to the design of cladding systems on buildings. It is also possible that heavy cladding systems will be used in the future for both lateral stiffening and increased damping in buildings [5,6,14,19,20,29]. Finally, it must be recognized that improper or inadequate design of building cladding can have a detrimental effect on the overall performance of structures during earthquakes.

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